Snowmass2021 - Letter of Interest

Extracting Physics from Natural Neutrinos with G3 Liquid Xenon Detector

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) *[Please specify frontier/topical group(s)]*

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Abstract:

The next-generation liquid xenon dark matter direct detection experiment will be in a unique position to detect both coherent elastic neutrino-nucleus scattering and neutrino-electron scattering. This will allow liquid xenon to make diverse contributions to various science programs, such as measuring Weinberg's angle $\sin^2\theta_W$ at the keV scale, searching for light sterile neutrinos, constraining the solar abundance problem, and studying neutrino propagation from core-collapse supernovae. This LOI will outline the scientific reach as well as the capabilities of the next-generation liquid xenon direct detection project to study neutrinos from natural sources.

1. Introduction

The third generation (G3) liquid xenon (LXe) direct detection (DD) experiment would be in a unique position to probe physics from natural neutrinos through both the neutrino-electron elastic scattering channel in the keV-MeV range and Coherent Elastic ν-nucleus Scattering (CEνNS) channel in the $E_\nu > 5$ MeV range. Hence LXe has four clear advantages over other technologies in terms of natural neutrino measurements:

1. High CEνNS rate due to the A^2 dependence.
2. Sub-keV energy threshold. LXe-based Time-projection chambers (TPC) are single-electron sensitive.
3. Discrimination between electronic recoil (ER) versus nuclear recoil (NR) at the keV scale.
4. Low radioactive backgrounds.

2. Precision Measurement of Solar Neutrinos

2.1. *pp neutrinos*

pp neutrinos account for 86% of all neutrinos emitted by the Sun. LXe TPCs observe the pp neutrinos via electronic recoil interaction. A G3 experiment will not only improve the measurement of solar neutrino luminosity, but also provide an independent constraint for Weinberg's angle ($\sin^2\theta_W$) [1]. A precise measurement of $\sin^2\theta_W$ was made at LEP (Large Electron-Positron Collider) at the GeV scale. The Standard Model renormalization group extends the prediction of this parameter to be 0.2387 at keV - MeV scale, but the current lowest measurement of $\sin^2\theta_W$ was only made down to 2.4 MeV [2]. pp neutrinos will yield an unprecedented constraint at the keV scale.

Borexino provides the best measured pp neutrino flux: $(6.1\pm0.5)\times10^{10}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ ($\sim 9.5\%$ uncertainty) [3]. One challenge of using LXe technology to observe pp neutrinos is the presence of ^{136}Xe isotopes which undergo $\beta\beta$-decays with an endpoint of 2.3 MeV. Although the ^{136}Xe spectrum dominates over pp at high energy, it falls rapidly below 20 keV [4]. With relativistic random phase approximation correction applied [5], the expected ER rate from pp neutrinos is $\sim$ 92 counts per 1000 tonne-days in the 0-15 keV range (780 counts per 1000 tonne-day in the full range). Hence, a 150 tonne-year exposure would reduce the statistical uncertainty in the $\sin^2\theta_W$ measurement down to 1.4% for the energy transfers in the range of 0-15 keVee. This is a significant step in precision.

2.2. *^{8}B neutrinos*

Anomalous results in short-baseline oscillation have stirred interest in probing light sterile neutrinos in the eV/c^2 mass range. According to the MSW-LMA (Mikheyev-Smirnov-Wolfenstein large mixing-angle) model, there is an upturn of ν_e survival probability from the matter-enhanced region (> 10 MeV) to vacuum dominated (< 1 MeV) region. When combined with the neutrino-electron scattering data from SNO, Super-Kamiokande, and Borexino, precision measurements of ^{8}B neutrino induced CEνNS in LXe G3 DD will constrain ν_e survival probability in the 5-15 MeV range. A significant deficit from the theoretical prediction would be possible to interpret as evidence of active-to-sterile neutrino oscillation [6].

Precise ^{8}B measurement through neutral current may also solve the solar abundance problem: a prediction made by the Standard Solar Model (SSM) using the recent helioseismology data cannot describe the present-day sun. Since ^{8}B flux is sensitive to the metallicity, a G3 experiment could help rule out solar models with various metallicities.

The current best measurement of ^{8}B neutrino flux from all active flavors is provided by SNO: $\Phi_{8B} = (5.25\pm0.20)\times10^6\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ ($\sim 4\%$ accuracy) [7]. LXe DD is able to obtain a clean sample of ^{8}B CEνNS events free of any physical background contamination, thanks to its discrimination power. However, since ^{8}B CEνNS signal appears near the thresholds, the expected count varies a lot depending on detector thresholds. G3 can reach higher statistics than the current generation with an improvement in signal detection efficiency. For example, an LZ-like detector would need 312 tonne-yr of exposure to bring the statistical uncertainty down to 4% using (S1 3-fold + 3 e^-) detector thresholds, while an improved detector with $g_1 = 0.15$ and $\tau_{\mathrm{ELIFE}} = 1\ ms$, will only need 169 tonne-yr of exposure with the same thresholds.

2.3. CNO neutrinos

For the SSM, less than 1% of solar neutrinos are produced by the CNO cycle, but the luminosity fraction is sensitive to the metallicity of the Sun. A precision measurement of CNO flux in the keV-MeV range will rule out various high/low metallicity solar models. With an expected CNO rate of 12.3 counts per tonne-yr, G3 is capable of measuring CNO neutrinos through the electronic recoil channel if the $\nu\nu\beta\beta$ background from ^{136}Xe can be reduced by a factor of 1000 [8].

2.4. hep neutrinos

G3 LXe DD may claim the first-ever detection of *hep* neutrinos in the CEνNS channel. Although *hep* neutrino flux is two orders of magnitude lower than ^{8}B, its recoil energy is slightly higher than ^{8}B making a significant discovery possible via a likelihood-based spectrum fit. The challenge of reaching a significant observation in G3 LXe DD depends on an improved resolution in the 1-3 keVnr range.

3. Neutrino Detection from Core Collapse Supernovae

Core Collapse Supernovae (CCSNs) are expected to occur in the Milky Way at a rate of 1–3 per century. In the first 10 seconds of a core-collapse supernova, almost all of its progenitor's gravitational potential, O(10^{53} ergs), is carried away in the form of neutrinos. The one, only confirmed historic detection of these neutrinos has been in 1987 from SN 1987A. The burst of 25 neutrinos from SN 1987A created the field of extrasolar astrophysics, provided the first glimpses into the heart of a dying star, and created an international program to detect and coordinate the response to the next CCSN neutrino burst.

CCSN neutrinos, with O(10 MeV) kinetic energy, can interact via CEνNS, depositing O(1 keV) in detectors and serving as an early warning for the optical telescopes. LXe TPCs have been shown to achieve the low threshold and low background needed to detect these neutrino interactions. A CCSN CEνNS detection in a LXe TPC offers a unique contribution to physics. As the CEνNS mechanism is insensitive to neutrino flavor these detectors will provide complementary data to the larger charged current channel detectors. The signal in a LXe TPC can make a measurement of the total energy released in neutrino flux during the CCSN. Lastly, such a detector, with well-instrumented DAQ system, can generate a real time trigger signal to provide to the Supernova Neutrino Early Warning System (SNEWS) and the astrophysics community.

To increase the likelihood of detecting CCSN neutrinos, the next generation LXe TPC needs to have a high up-time, with a service life O(10 years), and a size O(10 tonnes). For this size, these detectors would get 10s–100s of interactions from CCSNs occurring in the Milky Way. An R&D campaign would need to be carried out to design and build components that would survive a usage life of O(10 years). Work is currently ongoing at G2 dark matter experiments to implement an additional real-time trigger for CCSN ν's and to incorporate them in the Supernova Neutrino Early Warning System (SNEWS). The data acquisition systems for the next generation LXe TPC should be designed and optimized for incorporation into SNEWS.

4. Atmospheric Neutrinos

While atmospheric neutrinos are well measured for energies above 1 GeV, their flux uncertainty remains high at the MeV scale. Below ~ 50 MeV, the interactions of these neutrinos are an important background in the search for relic neutrinos from supernovae [9]. Atmospheric neutrinos will produce NR via CEνNS in LXe with a recoil energy spectrum up to ~ 90 keVnr. However, with an expected rate of 0.056 counts per tonne-year, a spectrum measurement will require a large-scale LXe target, at the hundreds of tonnes scale.

5. Conclusion

The G3 LXe experiment will open up a new realm within low-energy neutrino physics — its ability to observe both keV-scale neutrinos in the neutrino-electron scattering channel and MeV-scale neutrinos in the CEνNS channel is unprecedented. Along with other strengths of LXe technology, such as low radioactive backgrounds, and signal discrimination, G3 LXe will be competitive enough to measure natural neutrinos and potentially provide insights into new physics. Thus, in addition to dark matter searches, we should also consider the potential of opening up new directions in the neutrino frontier.

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