Snowmass2021 - Letter of Interest

DUNE-Beta: Searching for Neutrinoless Double Beta Decay with a Large LArTPC

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
☐ (TF11) Theory of neutrino physics
☐ (NF9) Artificial neutrino sources
■ (NF10) Neutrino detectors
■ (IF08) Noble Elements)

Authors:

J. Zennamo (Fermi National Accelerator Laboratory)[jaz8600@fnal.gov]
F. Psihas (Fermi National Accelerator Laboratory)[psihas@fnal.gov]
A. Mastbaum (Rutgers University)[mastbaum@physics.rutgers.edu]

Note: This LOI is presented on behalf of the authors, not in association with the DUNE collaboration.

Abstract:

A major challenge in searches for neutrinoless double beta decay is the design of detectors with large mass, low backgrounds, and percent-level energy resolution. A large-scale, high-precision LArTPC experiment such as DUNE could provide a unique opportunity for a sensitive neutrinoless double beta decay search. Through the addition of xenon as a dopant, a modified DUNE far detector module, or a similar detector, could achieve very high masses of double beta decay isotope, and thus high sensitivity to this decay. Doping a 10 kiloton-scale LArTPC detector with a candidate isotope at the percent level would produce a target mass on the scale of 100s of tons, while the monolithic volume would permit significant background reduction through fiducialization. Such a program, if pursued in the context of DUNE, could greatly enhance the physics program. This concept relies on realizing a number of new detector capabilities for large LArTPCs. In addition to enhancing physics reach and utilizing existing infrastructure, this concept opens a rich R&D program for the coming decades.

The discovery of the Majorana or Dirac nature of neutrinos, the neutrino mass ordering, and the possibility of CP violation in the neutrino sector are some of the most consequential mysteries of particle physics which remain to be uncovered, and they continue to be among the driving physics priorities for our field[1]. Current experiments are exploring the question of the nature of neutrinos through the search for neutrinoless double beta decay ($0\nu\beta\beta$), a rare process allowed only for Majorana neutrinos, with a variety of candidate isotopes and ongoing R&D to go from using hundreds of kg up to the ton scale[2]. In the coming decade, DUNE[3] is poised to definitively answer the questions of both the mass ordering and CP violation by studying the highest intensity neutrino beam ever produced, utilizing a massive detector and the next generation of experimental advancements.

The scale and infrastructure of the DUNE program could provide a unique opportunity to advance the $0\nu\beta\beta$ program beyond the ton scale and enable a 100-ton scale $0\nu\beta\beta$ experiment. The DUNE-β concept explores the modification of a DUNE-like detector module in order to make it sensitive to $0\nu\beta\beta$ signals. DUNE-β employs xenon, a candidate isotope for neutrinoless double beta decay, as a doping agent. Current studies consider LAr doped with ^{136}Xe at the 2% level, which would yield 300 tons of xenon-136 within a fully active 3 m fiducial volume.

Additionally, DUNE-β would require an enhancement to the baseline precision of the DUNE detector design to MeV-scale energy deposits, specifically in the context of energy resolution. This expansion of capabilities, if implemented in DUNE, could enable additional improvements to the broader DUNE physics program. These enhanced capabilities would enable improved precision in the exploration of solar neutrino mixing[4], enhanced sensitivity to low energy supernova neutrinos, and improved accelerator-based neutrino energy reconstruction[5]. This expansion of the potential physics program, and the requirements for its implementation introduces opportunities to push the limits of our detection and analysis techniques through a rich R&D program for the coming decade. There are three major R&D avenues central to demonstrate the feasibility of DUNE-β: low energy thresholds and energy resolution, background rejection, and xenon acquisition and injection. Progress made on any one of these topics over the coming decades would greatly enhance LArTPC technology, and the physics reach of the future LArTPC physics program.

Energy Resolution Challenges

The energy of the two-electron $0\nu\beta\beta$ signal, or $Q_{\beta\beta}$, from ^{136}Xe is 2457.8 keV. Experiments utilizing LArTPCs have recently begun to explore the MeV-scale regime with promising results[6–8], but R&D is necessary to achieve and demonstrate sufficiently accurate energy resolution at $Q_{\beta\beta}$. The target energy resolution for $0\nu\beta\beta$ experiments is typically near the percent level, but additional considerations regarding event rates and background rejections will impact this target. Measurements of the energy resolution for LArTPCs in the 1–3 MeV energy region will be required to demonstrate the feasibility of this concept, as well as alternatives for improvement. One such alternative is the addition of dopants into the liquid argon, with favorable effects for signal detection efficiency. It has already been demonstrated that the introduction of xenon into liquid argon increases the ionization yields, this effect is expected to be a 13%[9] increase in 2% xenon-doped LAr, which in turn can improve the energy resolution at the MeV scale[8]. Photo-ionizing dopants have been shown to convert the scintillation light to ionization charge[10]. The introduction of these dopants for light-to-charge conversion would enabling a higher precision ionization-only MeV-scale energy measurement. Further study of these techniques for application in a large LArTPC could lead to their application in any of the DUNE modules or other large LArTPCs, enhancing overall performance.

In order to detect and measure this signal, R&D is required to enable a detection threshold below 2.4 MeV. As a benchmark, DUNE is currently projecting DAQ thresholds for its first three modules incompatible with the low energy thresholds required for $0\nu\beta\beta$ detection, as it is currently projected that the rates below a threshold of 5-7 MeV would be higher than the DAQ design would allow[4;11]. It is possible that new improvements in triggering algorithms, such as those being pursued with machine learning[12], may aid in lowering these thresholds. Another possibility to address the energy threshold challenge is to take advantage of the lower noise expected from pixel readout electronics. Next generation pixelated readouts have demonstrated they are able to surpass the noise reduction that wire readouts can achieve[13;14]. Due to the constraints on power consumption of pixelated readouts these are required to be zero suppressed and with the low occupancy of a deep underground detector they create a small data-foot print when reading out data continuously.

Backgrounds

The main backgrounds expected in the energy range relevant to $0\nu\beta\beta$ come are signals from solar neutrinos[4], spallation products[15], as well as radioactive decays either from the detector materials or external to it. Detailed studies of background mitigation strategies are currently underway along with a complete characterization of these backgrounds. There are three key areas where R&D will be essential to mitigating these backgrounds: detector design optimization, utilization of underground argon, and new analysis techniques.

This concept leverages the massive scale of these detectors by effectively eliminating of surface radioactivity backgrounds through fiducialization. There are practical trade-offs that need to be studied to demonstrate this is the most practical design. As the detector grows electric-field non-uniformities become larger and could contribute to additional energy smearing. Further, very long drift distances can lead to charge attenuation through electronegative contaminants, which could have a impact on the design of a LAr purification system.

Careful study of the background contributions from the ^{39}Ar and ^{42}Ar present in the LAr will also be necessary. While ^{39}Ar is not of concern due to its low beta-endpoint, the ^{42}K, originating from ^{42}Ar decays, has a beta spectrum that overlaps with our $Q_{\beta\beta}$. A possible mitigation strategy currently under study would be the use underground argon which is naturally depleted in ^{42}Ar (and ^{39}Ar)[16].

Xenon Acquisition

The success of this concept relies on the acquisition of xenon in amounts that are challenging to acquire through current commercial capabilities. Our initial studies use two baseline assumptions for the 2% Xe doping: (1) using 900 tons of natural xenon, yielding 80 tons of ^{136}Xe or (2) doping at 2% with 90% enriched ^{136}Xe, which would require 10.4 ktons of natural xenon to be enriched. Ongoing research into xenon recovery using metal-organic frameworks[17;18] provide a promising path forward. Developing these techniques further would allow for room temperature extraction of xenon from the ambient atmosphere. Once these quantities of xenon are secured it needs to be efficiently mixed into the almost 20-kton of LAr that fills the cryostat. Initial concepts have been floated for how to do this, but most techniques have focused on significantly lower doping fractions. The long term stability of the xenon in the LAr will also need to be studied. Past work has shown that xenon doping at the 1.6% level is stable[19], but this requires further study in the context of modern LAr filtration techniques.

Conclusion

Prioritizing multi-measurement projects that enable R&D into the latest technologies is critical to broaden the opportunities for discovery and the physics output of our field. The DUNE-β concept could extend the physics program of DUNE and the LArTPC program at large into the MeV-scale energy region, enhancing neutrino energy reconstruction capabilities and enabling a DUNE-like detector to perform a hundred ton-scale $0\nu\beta\beta$ search. **This concept provides a platform for discovery in low energy physics as well as a rich R&D program for the coming decade.**

References

[1] S. Ritz *et al.*, “Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context.”

[2] M. J. Dolinski, A. W. Poon, and W. Rodejohann, “Neutrinoless Double-Beta Decay: Status and Prospects,” *Ann. Rev. Nucl. Part. Sci.*, vol. 69, pp. 219–251, 2019, arXiv:1902.04097.

[3] R. Acciarri *et al.*, “Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE),” 2015, arXiv:1512.06148.

[4] F. Capozzi, S. W. Li, G. Zhu, and J. F. Beacom, “DUNE as the Next-Generation Solar Neutrino Experiment,” *Phys. Rev. Lett.*, vol. 123, no. 13, p. 131803, 2019, arXiv:1808.08232.

[5] W. Castiglioni, W. Foreman, I. Lepetic, B. Littlejohn, M. Malaker, and A. Mastbaum, “Benefits of MeV-Scale Reconstruction Capabilities in Large Liquid Argon Time Projection Chambers,” 6 2020, arXiv:2006.14675.

[6] R. Acciarri *et al.*, “Demonstration of MeV-Scale Physics in Liquid Argon Time Projection Chambers Using ArgoNeuT,” *Phys. Rev.*, vol. D99, no. 1, p. 012002, 2019, arXiv:1810.06502.

[7] R. Acciarri *et al.*, “Improved Limits on Millicharged Particles Using the ArgoNeuT Experiment at Fermilab,” 2019, arXiv:1911.07996.

[8] W. Foreman *et al.*, “Calorimetry for low-energy electrons using charge and light in liquid argon,” *Phys. Rev.*, vol. D101, no. 1, p. 012010, 2020, arXiv:1909.07920.

[9] S. Kubota, A. Nakamoto, T. Takahashi, S. Konno, T. Hamada, M. Miyajima, A. Hitachi, E. Shibamura, and T. Doke, “Evidence of the existence of exciton states in liquid argon and exciton-enhanced ionization from xenon doping,” *Phys. Rev. B*, vol. 13, pp. 1649–1653, Feb 1976.

[10] J. A. LaVerne, A. Hitachi, J. J. Kolata, and T. Doke, “Scintillation and ionization in allene-doped liquid argon irradiated with ^{18}O and ^{36}Ar ions of 30 mev/u,” *Phys. Rev. B*, vol. 54, pp. 15724–15729, Dec 1996.

[11] B. Abi *et al.*, “Deep Underground Neutrino Experiment (DUNE), Far Detector Technical Design Report, Volume IV Far Detector Single-phase Technology,” 2020, arXiv:2002.03010.

[12] Y. Jwa, G. Di Guglielmo, L. P. Carloni, and G. Karagiorgi, “Accelerating deep neural networks for real-time data selection for high-resolution imaging particle detectors,” in *2019 New York Scientific Data Summit (NYSDS)*, pp. 1–10, 2019.

[13] D. A. Dwyer *et al.*, “LArPix: Demonstration of low-power 3D pixelated charge readout for liquid argon time projection chambers,” *JINST*, vol. 13, no. 10, p. P10007, 2018, arXiv:1808.02969.

[14] R. Acciarri *et al.*, “Noise Characterization and Filtering in the MicroBooNE Liquid Argon TPC,” *JINST*, vol. 12, no. 08, p. P08003, 2017, arXiv:1705.07341.

[15] G. Zhu, S. W. Li, and J. F. Beacom, “Developing the MeV potential of DUNE: Detailed considerations of muon-induced spallation and other backgrounds,” *Phys. Rev.*, vol. C99, no. 5, p. 055810, 2019, arXiv:1811.07912.

[16] G. Giovanetti *et al.*, “Applications for Underground Argon,” Snowmass 2021 LOI, arXiv:Snowmass 2021 LOI.

[17] S. K. Elsaidi, D. Ongari, W. Xu, M. H. Mohamed, M. Haranczyk, and P. K. Thallapally, "Xenon recovery at room temperature using metal-organic frameworks," *Chemistry-A European Journal*, vol. 23, no. 45, pp. 5. 10758–10762, 2017.

[18] D. Banerjee, A. Cairns, J. Liu, R. K. Motkuri, S. K. Nune, C. A. Fernandez, R. Krishna, D. Strachan, and P. Thallapally, "Potential of metal-organic frameworks for separation of xenon and krypton.," *Accounts of chemical research*, vol. 48 2, pp. 211–9, 2015.

[19] S. Kubota, A. Nakamoto, T. Takahashi, S. Konno, T. Hamada, M. Miyajima, A. Hitachi, H. Shibamura, and T. Doke, "Ionization yield in xenon-doped liquid argon," *Physics Letters A*, vol. 49, no. 5, pp. 393 – 394, 1974.