Snowmass LOI: Search for Heavy Sterile Neutrinos Using ^{39}Ar Beta Decays in Large LArTPC Detectors

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1 Introduction

The Deep Underground Neutrino Experiment (DUNE) [1–3] at the Long-Baseline Neutrino Facility is an international project that will be the largest particle physics experiment ever built in North America. The DUNE project will use massive liquid argon time projection chambers (LArTPCs) to address fundamental questions such as the origin of the matter/antimatter asymmetry in the universe. DUNE's CP violation measurement is key to addressing this question, and involves investigating accelerator neutrinos ($\sim$1 GeV) undergoing flavor oscillations over a long baseline ($\sim$1300 km). In addition to this measurement involving reconstruction of GeV-scale particles, DUNE has a broad MeV-scale physics program planned as well, including study of supernova/solar neutrinos.

Another MeV-scale physics measurement that can be carried out at DUNE is a heavy sterile neutrino search performed by detecting "kinks" in beta decay spectra, providing a handle on $|U_{e4}|^2$. These features are normally present in beta decay spectra due to mixing between the three Standard Model neutrinos [4], but primarily lead to spectral distortions very close to the end point. A heavy sterile neutrino search can be carried out at DUNE using ^{39}Ar beta decays. The large size of the DUNE far detector and use of atmospheric argon (^{39}Ar beta decay rate of 1 Bq/kg [5]) will lead to $\mathcal{O}(10^{19})$ decays within the detector over the lifetime of the experiment, providing abundant statistics for the measurement.

Reconstruction of ^{39}Ar beta decays has been previously carried out at MicroBooNE [6], a LArTPC neutrino experiment at Fermilab, demonstrating that low thresholds (roughly 100 keV) and good energy resolution from low TPC noise levels (roughly 50 keV) are achievable in large LArTPC detectors [7]. These results have been confirmed at ProtoDUNE-SP [8, 9], the prototype detector for the DUNE single-phase far detector design, though more detailed studies are currently in progress. In all cases, only the S2 ionization signal has been used in the energy reconstruction of the ^{39}Ar beta decays. The low thresholds and good energy resolution associated with S2 ionization signals, combined with the ^{39}Ar Q value of 565 keV, will allow for a search for sterile neutrinos in the 20 keV to 450 keV mass range at DUNE.

While a full sensitivity study has not yet been performed, significant improvement in the global limits in this sterile neutrino mass range is expected [10, 11]. The DUNE sterile neutrino search mass range is complementary to the searches by KATRIN [12] and follow-up experiment TRISTAN [13], which can look for heavy sterile neutrinos in the 1 keV to 18 keV mass range by making use of an enriched source of ^{3}H and a MAC-E filter. A proposed heavy sterile neutrino search more similar in mass range to the prospective DUNE search is the HUNTER experiment [14, 15], which will search for heavy sterile neutrinos in the 30 keV to 300 keV mass range by fully reconstructing K-capture decays from ^{131}Cs using magneto-optical trapping and recoil-ion momentum spectroscopy (RIMS). The global 99% CL upper limits (as of 2016) for $|U_{e4}|^2$ as a function of sterile neutrino mass m_4, along with the relevant search mass ranges for KATRIN/TRISTAN/DUNE, are shown in Fig. 1 (left).

This Letter of Intent summarizes various preliminary investigations and considerations relevant for a heavy sterile neutrino search at the DUNE far detector using ^{39}Ar beta decays. We wish to highlight this novel search as an exciting potential physics measurement to be made at the DUNE far detector that may benefit from additional detector development. In order to make use of the full $\mathcal{O}(10^{19})$ decays expected at DUNE, further development of the DUNE far detector DAQ may be necessary. Additionally, further light detector R&D may be needed to make use of S1 scintillation light signals for timing and energy measurements.

2 Preliminary Investigations and Considerations

In developing this concept for a prospective physics measurement at large LArTPC detectors such as the DUNE far detector, some preliminary investigations and considerations warrant discussion:

- A preliminary measurement is planned using ProtoDUNE-SP data. As ProtoDUNE-SP is a LArTPC detector located near the surface, there may be additional complications due to significant cosmogenic backgrounds and space charge effects [18]. Initial studies have shown that cosmogenic backgrounds are not so large as to drown out the ^{39}Ar signal completely, but also not negligible [7]. Space charge effects are large, but can be constrained using cosmic muons in the detector [9]. The impact from residual uncertainty on space charge effects remains to be investigated.

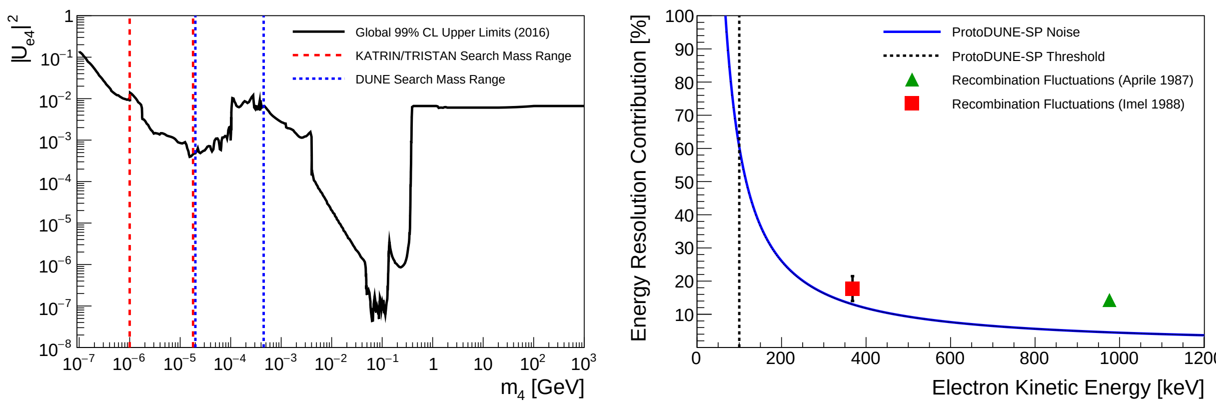

Figure 1: Global 99% upper limits (as of 2016) for $|U_{e4}|^2$ as a function of sterile neutrino mass m_4, assuming conservation of lepton number, along with expected KATRIN/TRISTAN/DUNE heavy sterile neutrino search mass ranges (left). Contributions to reconstructed ^{39}Ar beta electron energy resolution from noise (based upon preliminary studies at ProtoDUNE-SP) and from recombination fluctuations (based upon previous measurements in argon [16, 17]) at $\sim$500 V/cm if only S2 ionization signal is used (right).

- While space charge effects will be negligible at the DUNE far detector, cosmogenic backgrounds will still be present, though to a substantially smaller degree. Fully understanding the limitations from these backgrounds is an important future study.
- Other beta decays occurring in the liquid argon, such as those associated with ^{85}Kr, ^{42}Ar, and the ^{232}Th/^{238}U decay chains, could be included in the measurement as "kinks" should also be found in those spectra as well. This could improve the sensitivity of the measurement, though the other radiological decays will also lead to additional systematic uncertainties that must be studied in more detail.
- In addition to ProtoDUNE-SP, preliminary measurements can be made at the SBND detector of the SBN Program [19]. Similar complications exist for SBND as for ProtoDUNE-SP, though space charge effects will be an order of magnitude smaller. However, higher statistics may be available at SBND due to enhanced triggering if the DAQ is developed beyond the baseline plan.
- DAQ development is necessary to be able to use the full $\mathcal{O}(10^{19})$ ^{39}Ar beta decays expected at the DUNE far detector. This includes saving enough information to be able to reconstruct the energy and pulse shape of every single ^{39}Ar candidate as precisely as possible. Zero-suppressed readout, or prompt processing of streaming data that is later discarded, may be enough and achievable with minimal R&D.
- If S1 scintillation light is not used, the location of the ^{39}Ar beta decay in the drift direction can not be determined. However, it is still possible to account for impact from charge attenuation due to attachment to electronegative impurities (electron lifetime effects) in the measurement by making use of the fact that the decays should be uniformly distributed in the drift direction [7].
- Use of S1 scintillation light has not yet been explored, but may benefit the analysis by providing timing measurements for individual ^{39}Ar decays (less smearing due to electron lifetime effects) and also improve the energy resolution by greatly reducing impact from recombination fluctuations [20], shown in Fig. 1 (right). This may benefit from an enhanced light detector system at DUNE.
- ^{39}Ar beta decay is a first-forbidden unique decay, and as a result suffers from somewhat higher theoretical uncertainties than superallowed beta decays such as ^{3}H. However, the primary uncertainty is in the Q value (565 ± 5 keV) [21], and may not easily fake a "kink" in the spectrum that would arise from sterile neutrinos. Understanding the full impact of these uncertainties requires more study.
- Previous studies have not made use of the induction planes in reconstructing ^{39}Ar beta decays. While requiring their use would raise thresholds somewhat, this would allow reconstruction in 3D as opposed to 2D, potentially helping the vetoing of certain radiological/cosmogenic backgrounds.

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