Snowmass2021 - Letter of Interest

Searches for proton-decay with additional signatures from nuclear deexcitations and with precise timing from photon-detectors in large LArTPCs

Topical Group(s):

☑ **(NF3) Beyond the Standard Model**

☑ **(NF10) Neutrino detectors**

☑ **(IF02) Photon Detectors**

☑ **(IF08) Noble Elements**

☑ **(UF01) Underground Facilities for Neutrinos**

☑ **(UF03) Underground Detectors**

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Abstract

The intent of this LOI is to investigate the use of fast timing from photodetectors in large LArTPCs to identify nuclear de-excitations of ^{40}Ar after a baryon number violating process. This could be used to increase efficiency and reduce backgrounds in the search for proton decay.

Motivation and Intended Studies

The search for baryon number violation is a prime goal of particle physics and is being carried out in large underground detectors. Most of the current lifetime limits are affected by backgrounds, predominantly from the 100 events per kiloton year which arise from atmospheric neutrino interactions. The current best limits come from water detectors, but a promising way to reduce backgrounds is with a large liquid argon time projection chamber (LArTPC), almost all ^{40}Ar. A LArTPC provides the capability to image charged particles with mm-scale resolution. The concurrent detection of light in a photodetector system provides an opportunity to identify signatures from nucleon decay that are not present in neutrino interactions. Analysis strategies can then be tuned to both reduce background and increase efficiency. A photon-detection system can also measure energy calorimetrically, working as a crosscheck of the energy measured by the ionizing particles in a TPC and thus improving the energy resolution when both measurements are used together.

There are about one hundred nucleon decay modes [1] accessible to large underground liquid argon TPCs, similar to the DUNE Far Detector [2], or to the considered module of opportunity liquid argon TPCs, under consideration [3]. We see a valuable opportunity to combine signatures from particle and nuclear physics and take advantage of the fast and precise timing capabilities of a photon-detection system and the detailed pattern recognition capabilities of a LArTPC [4, 5, 6] to improve the sensitivity of future nucleon decay searches.

As an example, consider the mode $p \rightarrow \nu K^+$ [7]. For this mode, one looks for the K^+ signature via a short ionization track, followed primarily by $K^+ \rightarrow \mu^+\nu_\mu$ decay which makes an observable μ^+ track. The μ^+ decays to an observable positron. There are also other less likely K^+ decay modes. The kaon and its decay products can be reconstructed as images and the decay chain could be tested for kinematic consistency. Three potential backgrounds include 1) the large number of quasielastic atmospheric ν_μ interactions where the recoil proton is misidentified as a K^+, 2) production of K^+ by atmospheric neutrinos, and 3) neutrino production of K_L outside the detector which enter the LArTPC and charge exchange to a K^+.

There are several additional signatures of $p \rightarrow \nu K^+$ decay to investigate, mostly requiring fast timing from the photon system:

- The ^{40}Ar could often become an excited state of ^{39}Cl, with emission of deexcitation gamma rays. This nuclear process needs additional studies since any proton inside the ^{40}Ar can decay. The proton that decays might be deeply bound within the nucleus and the nucleus would be, at a minimum, left with an excitation energy much higher than the neutron separation energy and maybe even other separation energies. There is a possibility of even higher excitation if part of the decay energy is transferred to the nucleus. On the LArTPC response side, the detection of MeV-scale gamma-rays was demonstrated [7] with efficiency of 50% and energy resolution of 24% at 0.5 MeV, and with an efficiency of almost 100% and energy resolution of 14% at 0.8 MeV. If the gammas from $^{40}Ar \rightarrow {}^{39}Cl$

de-excitation are measured by the photon system, in addition to the TPC charge detection, we would have a new unique time-tag of the proton decay process.

- The product ^{39}Cl decays with a 56 minute half life to ^{39}Ar (feasible to tag in a deep detector). Then, ^{39}Ar decays 93% of the time to excited states and will give you characteristic gamma rays, roughly 54% of the time a 1.27 MeV gamma, 39% of the time a 1.52 MeV gamma and 46% of the time a 250 keV gamma (this one typically comes with the 1.27 MeV gamma).
- The K^+ lifetime is 12 ns, and a photon system with good timing could distinguish it from its decay products, as well as improve the identification of Michel electrons, from the 2 μs decay of μ's. In recently published results of the ProtoDUNE-SP liquid argon time projection chamber performance [8], a time resolution of 14 ns was achieved in the case of a single photon-detector channel. It is expected that photon-detector time resolution will improve as a square root of the number of independent channels, driving the resolution well-below 12 ns lifetime of K^+.
- Bound neutron decay to excited states of ^{39}Ar might also make deexcitation gamma.

Our intent is, therefore, to further study these signatures and to examine how the signal sensitivity will be further enhanced, and how backgrounds could be rejected more efficiently with additional information from nuclear deexcitations and with precise timing from photon-detectors in TPCs.

References

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