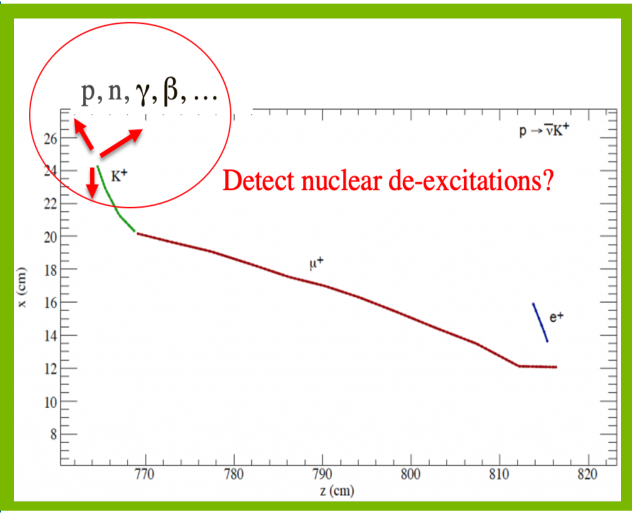
SEARCHES FOR PROTON-DECAY WITH ADDITIONAL SIGNATURES FROM NUCLEAR DEEXCITATIONS AND WITH PRECISE TIMING FROM PHOTON-DETECTORS IN LARGE LARTPCS



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Proton Decay Search: Motivation

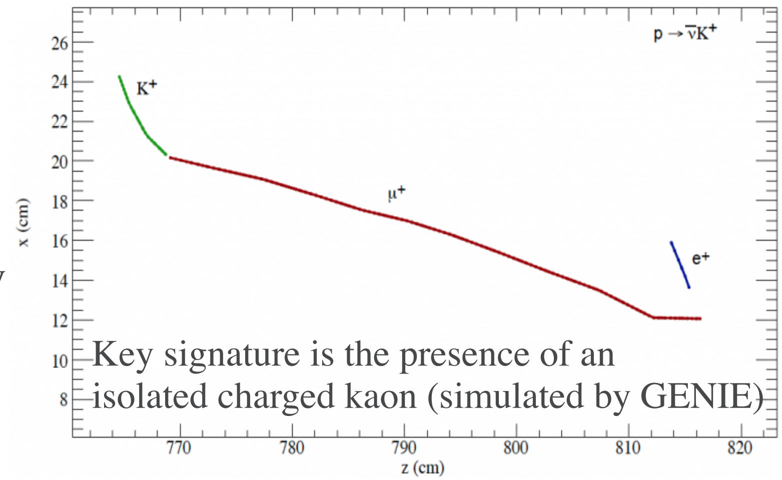
- The search for baryon number violation and the idea of unification of particles and forces are the prime goals of particle physics
  - -Motivate the nucleon decay experiments in large underground detectors.

- Particular modes of nucleon decay not known a priori although some are preferred by theoretical models
  - -Most of the current lifetime limits are affected by backgrounds, predominantly from the 100 events per kiloton year, from atmospheric neutrino interactions.
  - -The current best limits come from water detectors, but promise to reduce backgrounds comes with large LArTPCs, 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 (time “zero”, energy measurement via light).

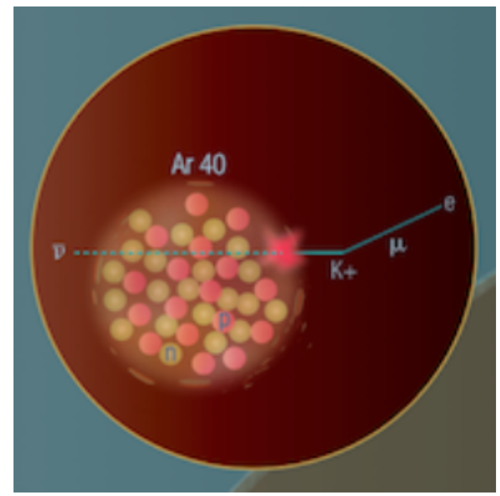
Illustrate With Example

- As an example, consider the mode $p \to \nu K^+$.
  - In LArTPCs, one looks for the K^+ signature via a short ionization track, followed primarily by $K^+ \to \mu^+ \nu_\mu$ decay which makes an observable μ+ track.
  - The μ^+ decays to an observable positron.

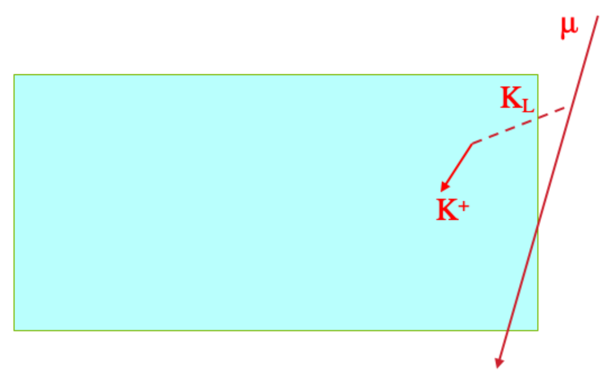


Key signature is the presence of an isolated charged kaon (simulated by GENIE)

- The kaon and its decay products can be reconstructed as images and the decay chain could be tested for kinematic consistency.



- Major potential backgrounds include:
  1) the large number of QE 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^+.



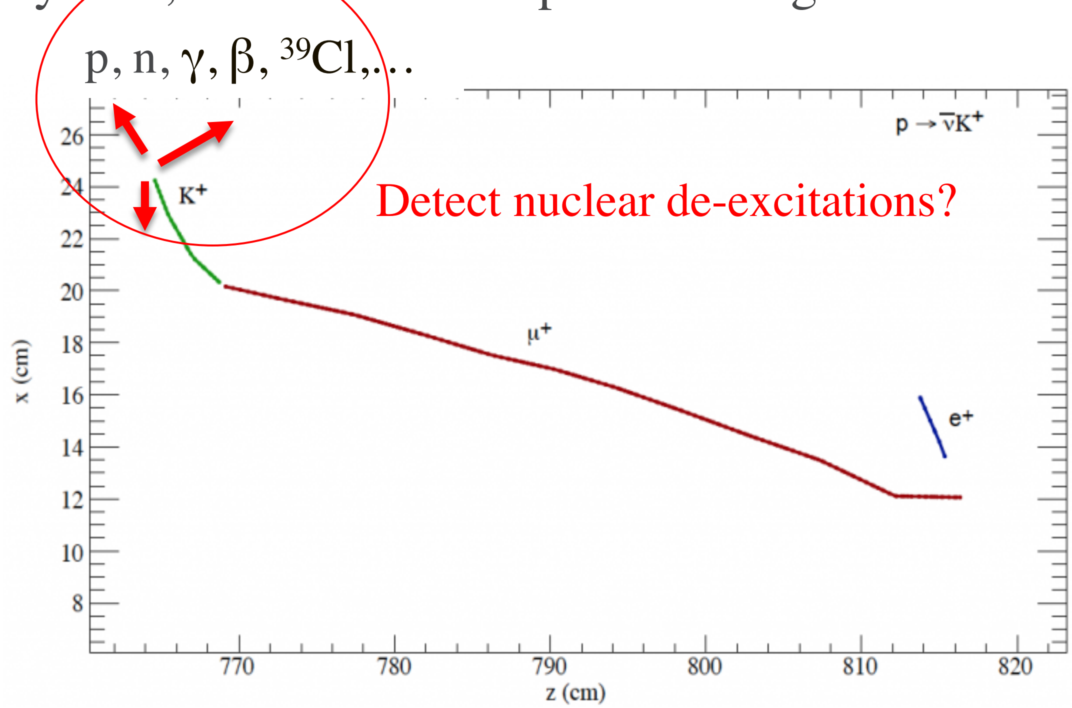
- Are there possibilities to further increase efficiency and reduce backgrounds in the search for proton decay?

Ideas to improve sensitivity

- Future large LArTPCs should explore new tools to reduce backgrounds and increase efficiency. We propose to
  1) Investigate nuclear de-excitation signatures, including daughter nuclei, associated with nucleon decay.
  2) Include improved photon detection system capabilities in consideration (time-0 capability and calorimetry).

- The intent of this LOI is to investigate opportunity to combine signatures from particle and nuclear physics, and to take advantage of the fast and precise timing capabilities of a photon-detection system, and the detailed pattern recognition capabilities of a LArTPC
  -Improve the sensitivity of future nucleon decay searches.

- This additional information from physics coupled to capable instrumentation should be used to increase efficiency and reduce backgrounds in the search for proton decay.



Additional Signatures: Nuclear De-excitations

- Search for the decay products from nuclear de-excitation of the residual radioactive daughter nuclei left after the disappearance of proton from ^{40}Ar nucleus.

- Expect ^{40}Ar to become often an excited state of ^{39}Cl, and to emit deexcitation γs
  -Any proton inside the ^{40}Ar can decay; if proton is deeply bound the nucleus would be, at a minimum, left with an excitation energy >> neutron separation energy.
  -The neutron separation energy in ^{39}Cl is 8.1 MeV; if the excitation energy is below that we expect some fast deexcitation gamma rays and then the 56 min β-decay to ^{39}Ar.

- The proton separation energy in ^{40}Ar is 12.5 MeV (binding energy of the least bound proton in ^{40}Ar)
  -If a proton from much deeper shell decays, the energy difference available to rearrange the nucleus might be way above the 8.1 MeV in ^{39}Cl (or maybe even > 10.2 MeV of proton separation energy in ^{39}Cl): single or multiple n, p may be ejected.
  -May expect a non-negligible fraction to end up in excited ^{38}Cl or ^{38}S and other things.

Some of possible daughter nuclei

Symbol	A	Z	N
40Ar	40	18	22
39Cl	39	17	22
38Cl	38	17	21
38S	38	16	22

- Low-energy/nuclear physics is not implemented in GENIE; currently used to model Kaon interactions in LArTPC
  -Perhaps it could be added to MARLEY or similar physics generators.
  -Another example where the collaboration with Nuclear Physics might be beneficial.

Additional Signatures: TPC with capable photon detection system

- Observing decay products from nuclear de-excitation (p, n, γ, β, …) by photon detector, in addition to the TPC charge detection, would provide a new unique time-tag of the proton decay process.

- In $p \rightarrow \nu K^+$ example the K^+ lifetime is 12 ns, and a photon system with good timing could distinguish K^+ 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 LArTPC (arXiv:2007.06722), a time resolution of 14 ns was reported for the single photon-detector channel.
  - -It is expected that photon-detector time resolution for N independent channels will improve as $\sim\sqrt{N}$, driving the resolution well-below 12 ns lifetime of K^+, perhaps down to ~6 ns.
  - -This approach assumed an efficient LAr scintillation light collection in future large LArTPCs, to observe nuclear de-excitations, followed by K^+ decay.

- These assumptions need further studies.

Summary

- An experimental observation of proton decay would be a spectacular proof of Grand Unification.

- Future large LArTPCs should explore new tools to reduce backgrounds and increase efficiency. We propose to
  1) Investigate nuclear de-excitation signatures associated with nucleon decay.
  2) Include improved photon detection system capabilities in consideration.

- 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.

- Original LOI is posted here:
  https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF10_NF3-IF2_IF8-UF1_UF3_Zelimir_Djurcic-188.pdf

BACKUP

Some Important Modes and Current Limits

- The single event lifetime in Liquid Argon after an exposure of 400 kT-yr is
- $107\ 10^{33}$ y * ε ($133\ 10^{33}$ y * ε) for proton (bound neutron) decay

Proton Modes (2020 best limit)		Neutron modes (2020 best limit)	
protons (10^{33} y)		bound neutrons (10^{33} y)	
❒ $e^+\pi^0$	24	❒ $e^+\pi^-$	5.3
❒ $\mu^+\pi^0$	16	❒ $\mu^+\pi^-$	3.5
❒ $\nu\pi^+$	3.6	❒ $\nu\pi^0$	1.1
❒ e^+K^0	1.0	❒ e^+K^-	0.017
❒ μ^+K^0	1.6	❒ μ^+K^-	0.026
❒ νK^+	8.2	❒ νK^0	0.52