The Necessity of DUNE Intranuclear Baryon Minus Lepton Number-Violating Searches for a World-Leading, Complementary Physics Program

A Discussion of Some Recent Progress in Searches Going Beyond Proton Decay, and Their Modeling

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Suggested Snowmass Topical Groups:

- (RF4) Rare Processes and Precision Frontier: Baryon and Lepton Number Violating Processes
- (NF3) Neutrino Frontier: Beyond the Standard Model
- (NF10) Neutrino Frontier: Neutrino Detectors

Abstract

To probe the origins of the baryon asymmetry, there must be a supported expansion of the Deep Underground Neutrino Experiment's (DUNE's) future physics program to specifically prioritize investigations of intranuclear baryon-minus-lepton-violating modes, including neutron-antineutron transformations *and other* (di)nucleon decay modes; this is necessary to create a world-leading and complementary physics program with ample scope *beyond* proton decay and neutrino oscillation studies. Here, we encourage the community to support scientists and students to pursue preliminary MC studies involving the construction of new, more accurate and encompassing rare process models, production of more powerful reconstruction algorithms, creation of more complete background simulations, and further development of massive automated analysis techniques in order to assess the true sensitivity reaches (with uncertainties) of DUNE across this compelling subspace of rare processes. Such searches could prove to be highly complementary to those of Super-Kamiokande and Hyper-Kamiokande, while some processes' expected high-multiplicity topologies may allow for uniquely high sensitivities if proper modeling, reconstruction, and particle identification are achieved going forward.

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The origin of the matter-antimatter asymmetry apparently obligates the laws of physics to include some mechanism of baryon number ($\mathcal{B}$) violation (BNV) via the Sakharov conditions[1]. Instead, however, perturbatively, the Standard Model (SM) *accidentally* conserves $\mathcal{B}$; in non-perturbative regimes at temperatures of $\gtrsim$ 10 TeV, electroweak sphalerons instead conserve "good" baryon minus lepton quantum numbers ($\mathcal{B}-\mathcal{L}$) while violating $\mathcal{B}+\mathcal{L}$[2], implying a form of BNV. Even still, as the primordial plasma moves through the electroweak phase transition, it is known that electroweak instantons (sphalerons) tend to "wash out" any preexisting baryon asymmetry without some other form of (typically) *higher-scale* lepton asymmetry production–perhaps near 10^{12} GeV, as is the case in classic leptogenesis[3]. Due to the effective impossibility of definitively testing for classic leptogenesis in any kind of "on shell" manner similar to the historic experimental confirmation of the $W^{\pm}$, Z^0, and Higgs, one must instead begin to investigate other *potentially observable* baryogenesis alternatives. If one proceeds by contradiction, one may conclude that a low-scale, possibly *post-sphaleron*[4–6] violation mechanism of "good" $\mathcal{B}-\mathcal{L}$ is both testable and necessary for proper baryogenesis. Though theoretically compelling[7], searches for such $\mathcal{B}-\mathcal{L}$-violating processes remain a largely under-explored topic in fundamental particle physics compared to other (potentially un)related rare processes.

$\mathcal{B}-\mathcal{L}$-violating $\Delta\mathcal{B}=2$ and $\Delta\mathcal{L}=2$ processes are thus of foremost importance in uncovering the nature of baryogenesis; those which can derive from an intranuclear origin with nucleonic degrees of freedom are critical for large underground experiments to understand. Note that proton decay modes, including those developing multilepton final states, do not share this property due to electric charge conservation, and thus do not directly give insights onto such questions. Beyond neutrinoloess double β-decay, which is generally more informative for theories of leptogenesis, the top candidate for a testable pursuit is neutron-antineutron transformation ($n\to\bar{n}$)[8–16], a key observable expected from low-scale post-sphaleraon baryogenesis[4;4;6] and many other scenarios[9;17–27], and which is but one of many possible dinucleon decay modes all carrying $\Delta\mathcal{B}=2$. Thus, such searches should be prioritized, and preliminary investigations into the viability of sensitivities among future large underground detectors to such processes should be supported. The unique nature of these signals, wherein the topology of the $\Delta\mathcal{B}=2$ process releases 4-5 mesons in a roughly spherically-symmetric manner, adds to this motivation in that the background contamination could be lower than other Standard Model (SM) and beyond Standard Model (BSM) processes with proper modeling and reconstruction.

The Deep Underground Neutrino Experiment (DUNE) promises one of the largest highly instrumented fiducial detector masses of any future large underground facility[28;29]. With 40 kt of liquid argon (LAr) some 1500m below Lead, South Dakota to shield against cosmic ray backgrounds, DUNE's immense wire readout particle ionization charge-collection system across four separate modules forms its three-dimensional LAr time projection chambers, allowing scientists to exploit bubble-chamber quality images[30–32] for world-leading precision physics studies of the SM and beyond. With potentially MeV-scale precision[33], the ability to distinguish γ and e species[34], low cosmic μ backgrounds, and very low LAr ionization kinetic energy thresholds for even heavy charged species such as protons (ps)[29;35], the overall physics potential of DUNE goes far beyond its initial purpose as a ν detector built to better constrain and measure oscillation parameters such as δ_{CP}. Indeed, the bubble-chamber-like capabilities of DUNE allow for observation of complex event topologies with potentially high multiplicities. Combined with state of the art detector reconstruction and particle identification (PID) methodologies, as well as a gargantuan number of intranuclear nucleons, there is great potential for the DUNE far detector to unlock the secrets behind rare processes.

Of course, given the future nature of DUNE, all sensitivity studies are currently relegated to simulations using generated Monte Carlo (MC) event samples. Using the GENIE MC event generator[36] and DUNE detector simulation and reconstruction software packages such as LArSoft[37], a first foray into sensitivity investigations for separating intranuclear $n\to\bar{n}$ from (predominately neutral-current) atmospheric neutrino backgrounds in the DUNE far detector was considered in[38]. However, there remains much work to be done. The dependencies of convolutional neural network's (CNN's) and other automated (machine learning) methods such as multivariate boosted decision trees' (BDTs') responses to various topological inputs is not entirely clear. The nature of these algorithms' responses to underlying choices in what are considered to be broadly consistent nuclear model configurations (NMCs) must be further studied to assess effective uncertainties, including those originating from disparate models of nuclear Fermi motion and final state interactions (FSIs) from (non)stochastic intranuclear cascades[39;40]. Given that the future event triggers for $n\to\bar{n}$ in DUNE (and others[41–43]) utilize the signal's expected region of interest (ROI) as informed primarily by the MC simulation of the process and its separation from background via automated methods, such dependencies are highly important, particularly when physical correlations are being ignored[1]; this is but one important component of the larger, still developing paradigm, which should include improved reconstruction and PID.

To explain this particular aspect in greater detail, let us begin by stating the obvious: there is actual importance in the maintaining of particularly relevant physical correlations in MC simulations which act to inform the detection of unknown (rare) processes. To illustrate this, consider Figs. 1[40]. Some correlations which have gone previously unexplored include the expected position of the intranuclear $\bar{n}$ annihilation following $n\to\bar{n}$ conversion, as shown at top left. Considering the $\{n,\bar{n}\}$ mass splitting which suppresses $n\to\bar{n}$ lessens as one hypothetically decreases the binding energy, a radial dependence is expected in the transformation probability beyond the simplistic assumption of the assumed Woods-Saxon nuclear density–indeed, such transformations are expected to occur predominately near the nuclear surface where n binding is low. Further, and as illustrated in the top central figure, given the strength of the annihilation cross section, the optical potential describing the Fermi motion of a previously converted $\bar{n}$ is expected to be deeper than that of normal nuclear matter, imbuing the converted $\bar{n}$ with higher available momentum. Similarly, due to $n\to\bar{n}$ occurring predominately on the surface of the nucleus, one may expect a reduction in the available Fermi motion-derived momentum; thus, simulations which are inherently *nonlocal* in their assumptions of Fermi motion (as is the case in the GENIE[36] default nuclear model) can lead to biases in any particular ROI. The (non)locality of a given nuclear model is shown by a decrease in (anti)nucleon momentum as one moves further out toward the nuclear envelope ($r\to R$), as shown in the bottom figures for two generators; if a hemicircular region is occupied in this parameter space, then no momentum-radius correlations are preserved.

The investigation in maintaining these physically relevant correlations can go even further, as one may expect fewer FSIs

[1] Further, the first analysis[38] utilized an intranuclear suppression factor for $n\to\bar{n}$ in ^{56}Fe[44] with a slightly inflated uncertainty rather than the suppression factor for ^{40}Ar, which has only recently been calculated[40].

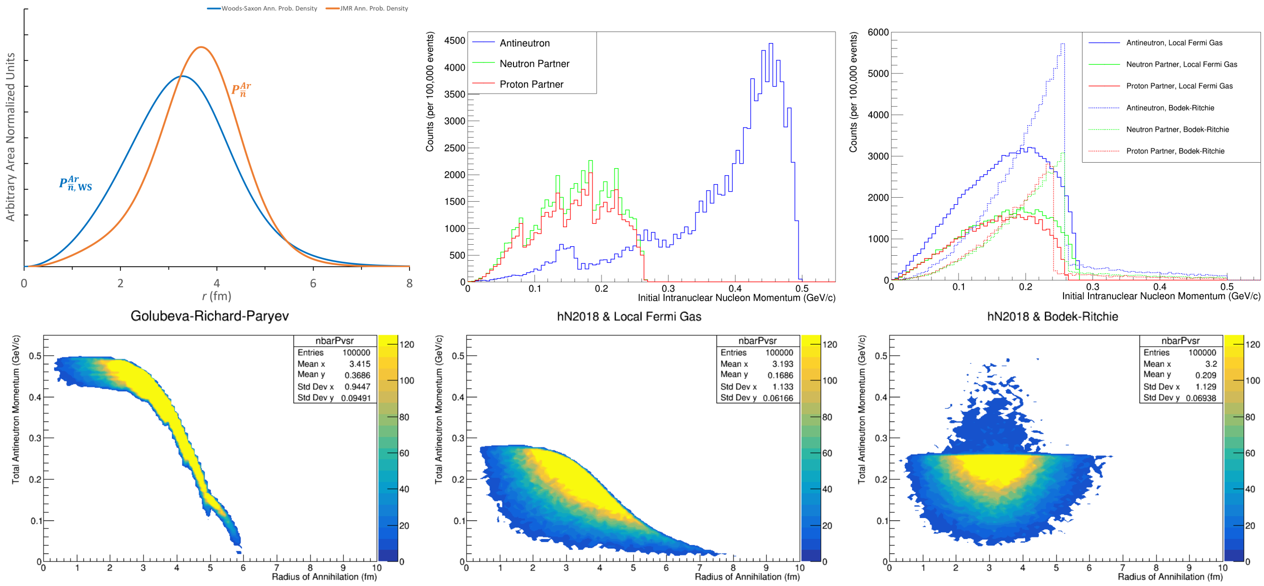

Figure 1: **Top Left**: Two curves are shown for various generator assumptions. In blue is the naive intranuclear radial position of $\bar{n}$ annihilation, a probability distribution generated by a Woods-Saxon nuclear density as presented in GENIE [36]. In orange is the modern, quantum-mechanically derived intranuclear radial position of annihilation probability distribution as developed in [40]. The scale is arbitrary. **Top Center**: The initial (anti)nucleon momentum distributions are shown using a local Fermi gas model with an additional $\bar{n}$ potential [40]. **Top Right**: The same for the GENIEv3.0.6 [36], showing a local Fermi gas model and the default nonlocal Bodek-Ritchie model. **Bottom Left**: A two dimensional plot of intranuclear $\bar{n}$ momentum-radius correlation is shown using a local Fermi gas and the newly-derived annihilation position distribution [40] (top left, orange). **Bottom Center**: The same using GENIEv3.0.6's [36] *local* nonrelativistic Fermi gas nuclear model of (anti)nucleon momentum and a Woods-Saxon nuclear density (top left, blue), showing good correlation. **Bottom Right**: The same using GENIEv3.0.6's [36] *nonlocal* Bodek-Ritchie relativistic Fermi gas nuclear model of (anti)nucleon momentum and a Woods-Saxon nuclear density (top left, blue), showing no positional correlation, and thus over-selecting high momenta.

experienced by annihilation-generated mesons due to reduced views on intranuclear scattering centers near the nuclear periphery. Also, when evaluating the $n \rightarrow \bar{n}$ signal's ROI (before consideration of further skewing due detector effects), choices across models of these FSIs can have a critical role in determining signal efficiencies through topological selection of high multiplicity events involving knock-out ps, which may be overproduced [40]. When considering outgoing mesons only, the nature of the ROI can be seen to remain disparate through the comparison of various NMCs across multiple (and single) generators, as shown in Figs. 2.

The importance of these correlations goes beyond the signal simulation; indeed, the same NMCs and correlations should be respected consistently across atmospheric neutrino background simulations. Iterating across the available NMCs, between and within single generators (for instance, GENIE [36]), and intermixing these together allows for the evaluation of uncertainties in a "universe" style approach, though going beyond simple knob turning; a project of this scale requires massive automated analysis techniques to be successful, especially given the nonreweightable nature of some of the more theoretically well-motivated nonstochastic FSI models employed. Such uncertainty evaluations will permit an understanding of the signal to background ratio, informing the the final expected sensitivities of DUNE to $n \rightarrow \bar{n}$: if this ratio remains stable across NMCs, then the minutia of certain physical correlations in simulation will be shown to be unnecessary; however, the opposite is the more likely case. Thus, this greatly encourages not only the evaluation of dependencies of automated analyses' (CNNs, BDTs) responses, but also the necessity of improved reconstruction. There have been great recent successes in machine learning being applied to PID, which was previously not included [38]; implementing a CNN score describing the probability of particular track's PID could better discriminate signal from background considering the unique high-multiplicity π-star expected to emanate from a nucleus after $\bar{n}$ annihilation.

By considering the above in greater detail into the future, DUNE sensitivities [35;45] to $\mathcal{B}-\mathcal{L}$-violating $\Delta\mathcal{B} = 2$ processes such as $n \rightarrow \bar{n}$ and related dinucleon decay modes are expected to greatly improve through enhanced physical modeling, reconstruction, and PID. Without these, the current expected lower limit for the mean $n \rightarrow \bar{n}$ oscillation period is 5.53×10^8 s[2], though uncertainties due to specific NMC choices remain under investigation, potentially lowering the sensitivities without other improvements. These steps are required in order for the collaboration to pursue truly complementary physics goals beyond proton decay and neutrino oscillation studies, enabling the broader particle physics community [41–43] to fully utilize future large underground detectors to better search for BSM physics, potentially informing us of our universe's origins.

[2] This does not include the recent intranuclear suppression factor calculation for ^{40}Ar.

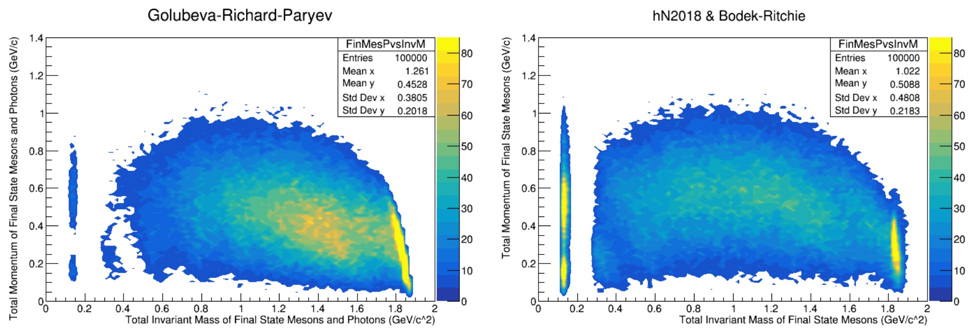

Figure 2: The final state mesonic/pionic parameter space (total momentum versus invariant mass) [43] after stochastic intranuclear transport of $\bar{n}$ annihilation generated mesons, compared for a few NMCs, not including detector effects. The ROI is generally considered to the be "hot-spot" in the lower right hand corner, implying the expected low Fermi momentum and high invariant mass derived from the annihilation of two nucleons creating a topologically spherical π-star; differences in these may lead to different detector signal efficiencies via automated methods. **Left**: a local Fermi gas model with an additional $\bar{n}$ potential and a full intranuclear cascade [39;40]. **Right**: GENIEv3.0.6 [36] using the default nonlocal Bodek-Ritchie relativistic Fermi gas and a full intranuclear cascade via the 2018 hN Intranuke model.

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