Future searches for free and bound $n \rightarrow \bar{n}$ transformations

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Abstract. Baryon number violation, a key, non-perturbative prediction of the Standard Model (SM) via electroweak instantons (sphalerons), has never been definitively observed. However, its relationship to baryogenesis is obscure, and, within the context of the SM, seems to require fine tuning and complex dynamics to occur mere instants after the chaos of the Big Bang began. Post-sphaleron baryogenesis (PSB), a SM extension first proposed by Babu et al. in 2006, seems to compellingly quell many of these theoretical conundrums while effectively predicting the baryon abundance, and simultaneously offering a tantalizing experimental observable: neutron–antineutron transformations ($n \rightarrow \bar{n}$). This rare event, a phenomena similar to meson oscillations, can be thought of as a form of dinucleon decay, and is hypothesized to occur for both the free and bound neutron; what's more, within the context of PSB, there exits an upper limit on the free neutron transformation rate. The subject of the relatedness of the free and bound rates promises a wealth of exciting nuclear and high-energy physics, and the complimentary nature of both types of experimental searches argues for their mutual necessity. In this paper, we briefly discuss the physics of the transformation, and our groups' plans to search for this critically important phenomena using both the free and bound neutron.

1. Introduction

It is known that the Standard Model (SM) is simultaneously a fantastically successful theory of the underlying nature of microscopic reality while remaining incomplete in several important regimes. These regimes include a microscopic and dynamic understanding the baryon ($\mathcal{B}$) asymmetry of the universe (BAU) along with the ultimate stability of matter itself. These two are possibly inextricably linked through beyond the SM (BSM) baryon minus lepton ($\mathcal{B}-\mathcal{L}$) number violating processes, a key requirement of the Sakharov conditions [1], the renormalizability of the SM [2], and post-sphaleron baryogenesis [3–5]. Such $\mathcal{B}-\mathcal{L}$ violating BSM processes generally fall under dinucleon or nucleon decay (NDK) searches, among them neutron-antineutron transformation ($n \rightarrow \bar{n}$) [4–6] and *arguably* proton decay (PDK).

Future high-energy probing experiments could potentially test theories predicting $n \rightarrow \bar{n}$, opening the door to the prospect of discovering the mechanism behind the BAU. Key among these include bright neutron sources, such as the European Spallation Source (ESS) for a free neutron search, and large underground experiments, such as the Deep Underground Neutrino Experiment (DUNE) and Hyper-Kamiokande (HK) for bound neutron searches (within argon and oxygen, respectively).

Free neutron and intranuclear transformation experiments are complementary both in their sensitivity to new physics and the interpretability of their results [6]. On a fundamental level, dimension $d = 9$, 6-quark operators can produce intranuclear transformations through a broader range of processes and with potential enchancement or suppression relative to free neutron experiments (see references in [6], especially [7]. As such, free neutron experiments provide a very precise and sensitive probe for neutron-antineutron transformations, and intranuclear experiments provide a "broadband" sensitivity to related dinucleon processes.

Because free neutron experiments can be designed to be "background free", they provide unambiguous discovery potential. Free neutron experiments also have (by controlling the magnetic field along the neutron trajectory, see Sect. 2) the ability to identify false positive results. This is in contrast to large underground experiments, for which a component of irreducible background due to high energy neutrinos is expected. A key question in this regard is to what degree the remarkable advances in tagging the interaction products in underground experiments such as Dune can be supported by detailed models of the nuclear dynamics (for example pion scattering and absorption) in target nuclei.

2. The free transformation

A number of neutron–antineutron transformation measurements have been performed both with free neutrons and via intranuclear transformation in large experiments deep underground (see Table 1), and there are several active programs today. For free neutrons, the transformation probability from an effective Hamiltonian H_{eff} coupling a pure neutron state $|n\rangle$ to an antineutron state $|\bar{n}\rangle$ is given by [6]:

$$P(n(t) = \bar{n}) \approx (t/\tau_{n-\bar{n}})^2 , \tag{1}$$

where $\tau_{n-\bar{n}} = 1/\delta m$, and δm is the transition matrix element

$$\langle \bar{n}|H_{\text{eff}}|n\rangle \equiv \delta m \tag{2}$$

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Table 1. Neutron-antineutron lifetime lower limits (90% CL).

Experiment	10^{32} n-yr	$\tau_m(10^{32}$ yr)	$R(10^{23}$/s)	$\tau_{n-\bar{n}}(10^8$ s)
ILL (free-n) [13]	n/a	n/a	n/a	0.86
IMB (^{16}O) [14]	3.0	0.24	1.0	0.88
Kamiokande (^{16}O) [15]	3.0	0.43	1.0	1.2
Frejus (^{56}Fe) [16]	5.0	0.65	1.4	1.2
Soudan-2 (^{56}Fe) [17]	21.9	0.72	1.4	1.3
SNO (^{2}H) [19]	0.54	0.30	0.25	1.96
Super-K (^{16}O) [18]	245	1.89	1.0	2.44 [1]

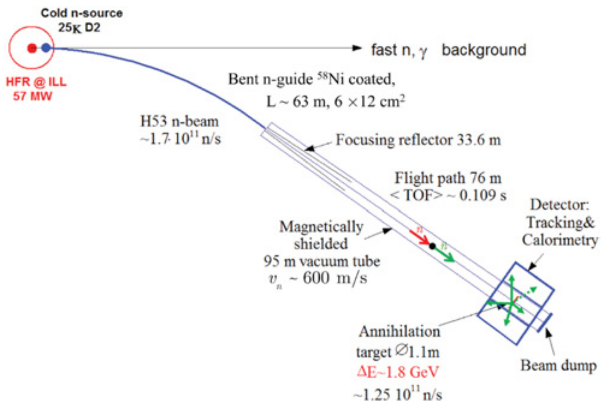

Figure 1. The cold neutron beam experiment [13] at the 58 MW research reactor at the Institut Laue Langevin in Grenoble. This experiment set the most stringent limits to date for neutron–antineutron transformations in free neutrons.

taken to be real. Formula 1 holds when we assume CPT symmetry, neglect the effect of neutron decay (true for cold neutron beams experiments) and the "quasi-free" approximation holds, where the change in the neutron phase "during flight" due to ambient magnetic fields and collisions with background gas are much smaller than one ($\Delta\phi \ll 1$). The basic strategy of a cold neutron beam experiment is to prepare a region in which the neutrons move with ballistic motion (free from perturbing magnetic fields, material walls and ambient gas) of length ℓ. After propagation through this "drift" region, the $\bar{n}$ amplitude will be approximately $(t_d/\tau_{n-\bar{n}})$, where now $t_d = \ell/v$, where v is the velocity of the cold neutrons. The cold neutron beam is then incident on a graphite target, where the $\bar{n}$ state will annihilate with effectively 100% probability. The resultant annihilation event produces a pion shower, which can be identified and tracked with a tracking calorimeter optimized to eliminate background processes which can mimic the pion shower. Because each incident neutron effectively samples the $\bar{n}$ transformation probability, with the probability going as t_d^2, the figure of merit for these experiments is Nt_d^2. with N being the total number of neutrons passing through the target.

The experiment performed at the Institut Laue Langevin, completed in 1994, was the most sensitive to date, producing a limit of $\tau_{n-\bar{n}} > 0.86 \times 10^9$ s [13]. The layout of this experiment is depicted in Fig. 1. The cold neutron beam emerged from curved guide system, effectively removing high energy backgrounds from the beam, and entered a conical reflector system 33.6 m in length, followed by the drift region and then a 100 µm thick, 1.1 m diameter, graphite target, and finally on into a beam dump. The target was surrounded by a tracking calorimeter with dimensions of about 4 m on a side, with an estimated $barn$ detection probability of $52 \pm 2\%$. The performance of this experiment has set the standard to date, with no candidate $\bar{n}$ events detected with 1 calendar year of running, for an integrated beam intensity on target of 1.25×10^{11} s^{-1}.

The ILL experiment demonstrates that cold neutron beam experiments can be designed to be background free, making them effectively limited by the drift time and the integrated intensity. Opportunities to increase both parameters exist in next generation experiments with neutron beams, leveraging the increased intensity available from modern neutron guide and optics technology and the potential availability of larger area beams with much greater intensity at next generation neutron facilities.

One such opportunity centers around a remarkable facility being proposed for the European Spallation Source, offering huge enhancements (two to three orders of magnitude enhancement) in the sensitivity of neutron–antineutron transformation probability. The proposed facility would utilize a beamport spanning the output of three normal cold neutron beams already integrated into the baseline design of the ESS (see Fig. 2). For the NNBar@ESS project, this beamport would be utilized for a neutron–antineutron transformation experiment by coupling the output of the beamport to a state-of-the-art, large area neutron focusing optic, which would utilize advances in the production of neutron reflectors to produce a gain of a factor of 30 or more in the flux relative to the ILL experiment. The neutron guide at ESS can be a factor of two to four longer as well, resulting in total sensitivity gains (including the increased beam area) of a factor of 200 to 600 for a three year experiment, relative to ILL [20]. Longer running should be possible, and implementing an optimized liquid deuterium moderator in the lower moderator position (not implemented during commissioning of the ESS) could result another factor of about two gain. An experiment which realizes these goals would likely set the standard for sensitivity for decades to come. Many aspects of the design concerns for a next generation cold neutron beam experiment are discussed in Phillips et al. [6].

Development work for this project and for alternative experiment designs under consideration are planned to take place at ILL (at the PF1b beamline for example) and at ANNI, the proposed particle physics beamline at the ESS [21]. The HIBEAM project would be sited on this beamline, and be dedicated to proto-typing concepts

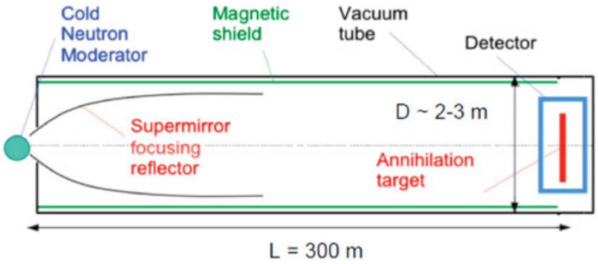

Figure 2. A simplified model of a cold neutron beam experiment at the large beam port at the ESS (NNBar@ESS). The projected ultimate sensitivity, after 3 years of running, is from 200 to 600 times that of the original experiment, depending on the details of the shielding optimization near the ESS moderator, using the current cold source design.

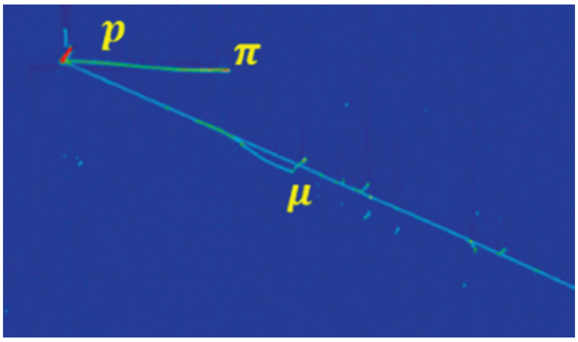

Figure 3. A charge current ν event in the μBooNE LArTPC detector showing excellent track resolution. A low energy, $\sim 25\,\text{MeV}$ proton, charged pion, and muon are identified. Adapted from [29].

for the full NNBar@ESS experiment and exploring other neutron transformation experiments. PF1b and HIBEAM also provide an opportunity to explore alternate approaches to the experiment discussed above, which optimize the neutron optics of a given neutron beam to preserve the quasi-free approximation through several collisions with the guide wall, by ensuring sufficiently "glancing" angles are achieved for typical neutron trajectories. These ideas may provide another path to comparable sensitivity [22].

3. The bound transformation

The primary searches for baryon violating processes have been completed in large detectors deep underground, and each has a potentially significant associated background of atmospheric neutrinos (ν_{atm}) where, respectively, electroweak neutral and charge current event topologies from large swaths of the ν_{atm} spectrum can obscure their true BSM signal. For example, in the previous search for intranuclear $n \to \bar{n}$ in the water-Cherenkov detector of Super-Kamiokande (SK) [23], a considerable background from an expected 24.1 ν_{atm} interactions on oxygen effectively removed any statistical significance from the observed 24 candidate events. None-the-less, this search remains the most far reaching of its kind, producing a lower limit for the intranuclear n lifetime in oxygen of $\tau_M = 1.9 \times 10^{32}\ yr$; when converted into a free mean $n \to \bar{n}$ time, $\tau_{n\to\bar{n}}$, through the conventional theoretical nuclear physics formalism [24–26], wherein

$$\tau_M = R\tau^2_{n\to\bar{n}}. \tag{3}$$

and with an appropriately calculated *suppression factor*, R, this lower limit becomes $2.7 \times 10^8\,\text{s} \approx 8.5\,\text{yr}$. This value can be contrasted with the predictions for the free mean $n \to \bar{n}$ time in [5], making it clear that a new landmark, sea-changing experiment(s) is necessary to further explore the pertinent parameter space for these phenomena. The value and derivation of R is a detailed topic, and would require quite a bit of discussion; however, suffice it to say that their values are quite stable and can be calculated using shell model techniques for several nuclei to within $\sim 20\%$ [26].

Enter DUNE (or, possibly, HK, though this will not be a focus of this proceedings), the future heart of American high-energy particle and ν physics, run by the Fermi National Accelerator Laboratory (Fermilab). Though the nature of the ν in all its complexities is the main driver behind this burgeoning international collaboration, just as well, the proposed technological advancements of DUNE's liquid argon time projection chambers (LArTPCs) *promise* a great leap forward in background discrimination capabilities for BSM searches. Prospects for DUNE reaching further than ever before for $n \to \bar{n}$ searches are supported, in the very least, by the substantial increase in detector mass over SK. More essentially, one should consider the unique capabilities of LAr in track resolution and particle identification, along with the distinctive event topologies of the *presumably* spherical "pion star" emanating from the $^{40}_{18}Ar$ nucleus after an intranuclear $n \to \bar{n}$ event and subsequent annihilation. Also, upon noting the possibility of detecting and reconstructing $\geq 25\,\text{MeV}$ kinetic energy protons in LArTPCs, like those seen in Fig. 3, one can readily recognize what fantastic feats LAr could achieve when compared to the higher energy thresholds required to observe such nucleon knock-out events in SK. These advantages clearly highlight the exceptional nature of DUNE's BSM parasitic search *potential*. For a $n \to \bar{n}$ search, it *could* be possible for DUNE to achieve a reach in the intranuclear n lifetime of $\sim 10^{35}\ yr$ with the observation of a single event in the presence of *convincing techniques* for *absolute* ν_{atm} background suppression; however, losses in efficiency, improperly categorized background events, and model uncertainties in the current DUNE simulation effort [27] collectively limit this reach by as much as nearly two orders of magnitude, hoping to better existing experimental limits [23] by a mere factor of five. This effectively disallows any possibility of an *actual* discovery. The work of our group concerning intranuclear $n \to \bar{n}$ analyses has produced promising results when contrasting signal with ν_{atm} background in Monte Carlo (MC), suggesting improvements could be made to [27] by requiring particular particle content (such as the aforementioned *reconstructable proton*) in final state event topologies within specific kinematic regimes, improving signal efficiency and background rejection rates. The convolutional neural network (CNN) [27] analysis forgoes such particle identification and utilizes only partial reconstruction for topological scrutiny; this creates a somewhat low signal efficiency, and is concerning considering its intention to serve as a triggering mechanism for future searches, implicitly limiting the BSM reach of DUNE. It has also become clear to our group

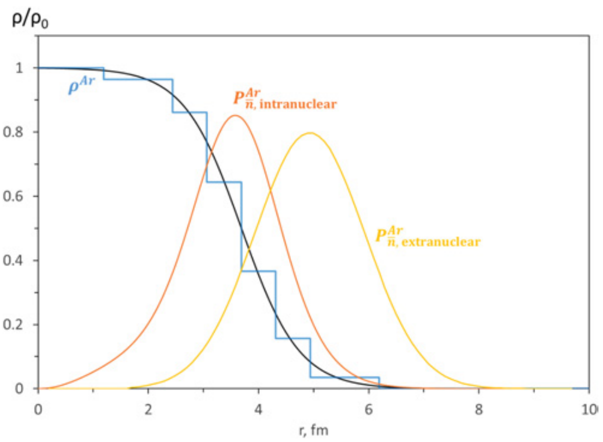

Figure 4. Using arbitrary normalizations for radial comparison purposes only, this plot shows $^{40}_{18}Ar$'s nuclear density distribution in black (approximated by the blue stepped histogram), the *approximate* radial annihilation probability distribution of extranuclear annihilation on $^{40}_{18}Ar$ in yellow (assuming similarity with [32]), and the same for an intranuclear annihilation in orange [33]. These distribution are shown as used in our group's internal intranuclear $n \rightarrow \bar{n}$ MC simulations, and represent extensions of our current work for the ESS NNBar collaboration in modeling of the free (extranuclear) transformation and subsequent annihilation on carbon [31,33]. Most pertinent to DUNE, the figure effectively shows differences between the current assumptions of [27], wherein the transformation and subsequent annihilation are supposed to occur along the density profile of the nucleus, and our modeling of the intranuclear annihilation position [30,32,33]. Though the effects and differences of these distributions are not yet entirely modeled or understood, it seems probable that such a distribution, when coupled with the low momentum dynamics of the nucleons near the surface of the nucleus, could lead to nontrivial aspherical event topologies.

that potentially first-order physics has been overlooked in the modeling of signal and background in [27], as seen in Fig. 4. For instance, because the $\bar{n}$ annihilation model used within GENIE [28] is *based* on ν interactions, the transformation probability and subsequent annihilation with the nearest neighbor nucleon within $^{40}_{18}Ar$ is assumed to depend on the radial density distribution of the $^{40}_{18}Ar$. However, quantum mechanically, it turns out that loosely bound n's are more likely to undergo $n \rightarrow \bar{n}$, meaning their momenta and final state topologies could be nontrivially affected; to state this explicitly, $n \rightarrow \bar{n}$ is likely to occur at the surface of the nucleus [30,33], and so background discrimination could decrease due to the apparently correlated directionality of the final state topology. Work is currently underway to include this effect in GENIE simulations. Also, and importantly, the default nucleon momentum distributions active within the current GENIE MC for $n \rightarrow \bar{n}$ and ν_{atm} events utilize rather simple, non-local, non-relativistic Bodek-Ritchie Fermi gas models. Correspondingly, considering the quantum mechanical inconsistency of the repetitive use of one-body nucleon momentum distributions for a single nucleus in MC when modeling an inherently two-body interaction like $\bar{n}N$ annihilation, the implementation of two-body momentum distributions could change the apparent visibility or invisibility of $n \rightarrow \bar{n}$ above background. It could also be helpful to complete a detailed study of other nontrivial nuclear effects on BSM signals and backgrounds, such as the addition of phenomenologically driven models of short-range nucleon-nucleon correlations, possibly leading to excesses within particular branching fractions.

While it is true that future DUNE data will indeed test and resolve theoretical nuclear physics models used in MC for $^{40}_{18}Ar$, presently these models can arguably only be tested by their overall consistency between and among themselves, effectively requiring a combination of various theoretical approaches. Regarding these, there exist a number of of perogatives for our group's future MC simulation work beyond [31,33]. In continuation of similar efforts discussed in [34], it is necessary that the simulation of new, reliable, ν_{atm} background samples within the DUNE ten kiloton LArTPC detector modules utilize cross sections for electron and ν scattering developed at LANL/ANL from ab-initio quantum Monte Carlo calculations. We hope to implement these calculated electromagnetic cross sections within GENIE, followed by a comparative validation against electron scattering data. This effort will be followed by similar steps for simulations in newer, independent, and novel generators such as the Giessen Boltzmann-Uehling-Uhlenbeck (GiBUU) Neutrino Event Generator [35] and the Wroclaw Neutrino Event Generator (NuWro) [36]. Further, we will integrate these specifically designed ν_{atm} event samples into the already highly-developed CNN [27] and multivariate boosted decision tree (ROOT TMVA) data analysis modules for feasibility studies of intranuclear $n \rightarrow \bar{n}$, to be followed by an integrated analysis across these samples, allowing for an eminent assessment of model uncertainties. Together, the utilization of GENIE, GiBUU, NuWro, and in-house generators for an updated, improved, more accurate simulation of $n \rightarrow \bar{n}$ events will allow for a proper assessment of the possibility of reducing ν_{atm} rates to or near zero, fully enabling DUNE's BSM physics discovery potential.

Together, all the previously mentioned nontrivial dependencies merit further, in depth studies to ascertain DUNE's true potential experimental reach. Understanding the complex interplay of these proposed phenomena with accurate ν_{atm} background simulation is key to justify the feasibility of BSM searches like $n \rightarrow \bar{n}$.

4. Conclusions

Both free and bound $n \rightarrow \bar{n}$ searches provide important probes for baryon number violating interactions. Next generation experiments offer a large increment in the sensitivity for detection of these processes, with the possibility of unambiguously discovering them and providing a consistent picture of their signature in a variety of nuclear systems as well as in the free neutron.

In all, these searches provide us with the means to closely study or even possibly eliminate entire theories of baryogenesis in a self-consistent and coherent manner, all while maintaining *true* access to the supposed energy scales which once may have permitted the initial matter-antimatter symmetry breaking mechanism to occur. This puts the *set* of future $n \rightarrow \bar{n}$ experiments in a truly unique position, one should be exploited to the fullest extent possible.

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