A Physics Upgrade to the GENIE Generator $n \rightarrow \bar{n}$ Module

Incubator: “nnbar_upgrade”

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The Importance of $n \rightarrow \bar{n}$

Baryogenesis still remains unexplained

- The Sakharov conditions require a source of baryon number violation, which so far has remained unobserved

High energy scale baryon number violation seems to not be the source of the baryon abundance

- Due to $B - L$ conserving instantons (sphalerons) which naturally wash out any asymmetry

The matter-antimatter asymmetry of the universe can be generated during a later epoch, perhaps under the guise of popular theories of *post-sphaleron* baryogenesis

- A key input to such theories are beyond Standard Model $\Delta B = 2, d = 9$, 6-quark operators which mediate observable $n \rightarrow \bar{n}$ transformation rates at rather low energy scales $\sim 10 - 100\ TeV$
  - The theory predicts a believable baryon abundance and *can be invalidated*, as there is an upper limit predicted on $\tau_{n \rightarrow \bar{n}}$ which *could* be reached by future experiments such as DUNE or Hyper-Kamiokande (intranuclear), or the European Spallation Source (extranuclear)
  - **Proper understanding of signals and backgrounds for these experiments will effect the future orientation of the baryon number violation community**

The observation of $n \rightarrow \bar{n}$ would be a definitive signal of the symmetry violating mechanism behind the baryon asymmetry of the universe, rendering leptogenesis unnecessary

- Secondarily, most all popular leptogenesis schemes are technically infallible with current and future experimental searches, no matter the measured value of δ_{CP} or the Majorana nature of the neutrino

Current GENIE $n \to \bar{n}$ Simulation Overview

Currently, the $n \to \bar{n}$ generator creates events according to…

1. An annihilation position that goes as a Woods-Saxon distribution
   - A position is thrown
   - A neutron/antineutron is generated at this point
   - A nucleon annihilation partner is generated at this point
2. Two nucleons' momenta thrown from a Bodek-Ritchie distribution with a short-range correlation tail
3. The pertinent phase space is then divided among annihilation products (mainly pions) derived from (slightly changed) branching ratios originally found in Super-Kamiokande's $n \to \bar{n}$ publication
   - Uses altogether ~ 20 channels $\bar{n}n$ and $\bar{n}p$ annhilation
4. Nuclear transport is then conducted by Intranuke hA

For a nice description, see Chapter 12 the current GENIE-v3 (draft) manual

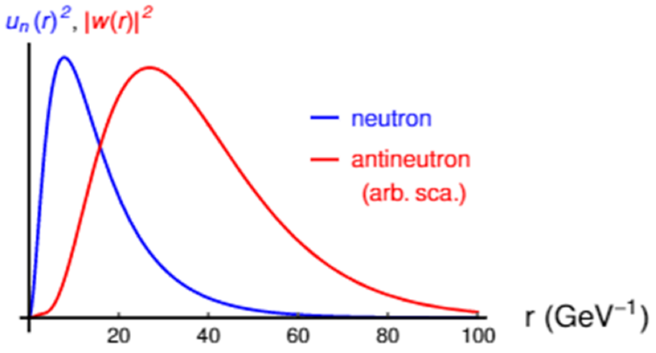
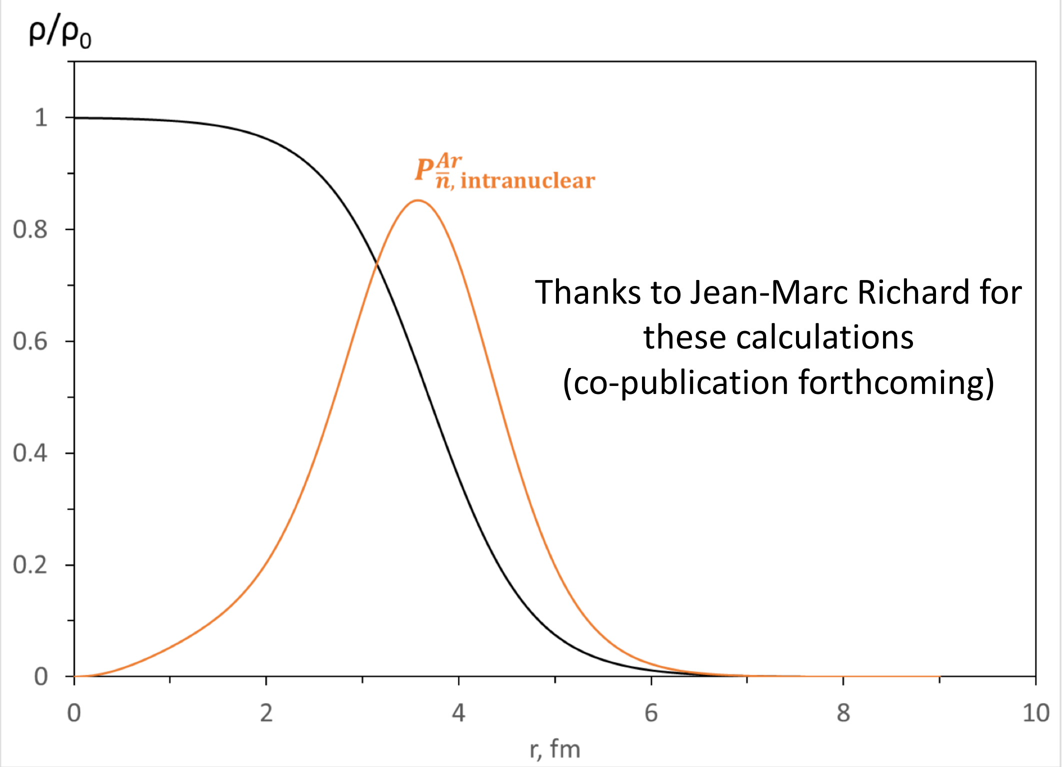


FIG. 1. The antineutron radial distribution (red) (arbitrarily rescaled to fit the figure) as compared to the nominal neutron distribution (blue).



Suggested Enhancements to Current Physics Simulations

1. The annihilation radius is known not to go as a Woods-Saxon density distribution for the nucleus

This is due to the fact that the binding energy of a n is not constant throughout the nucleus

- Thus, approaching the surface of the nucleus, a n is more likely to oscillate into an a $\bar{n}$ due to lessening mass difference in the effective Hamiltonian (see upper left figure)
- When convolved with the distributions of possible annihilation partners, we find that the annihilation is still likely to happen at the surface of the nucleus (see lower left figure)
  - The maximum of the radial annihilation probability distribution sits around the radius of half density (the surface)

Thus, the current assumptions could over-emphasize the sphericity of the event topologies, a key assumption behind the use of current CNN/BDT analysis schemes for signal/background separation

Suggested Enhancements to Current Physics Simulations (cont.)

2. A single nucleon momentum distribution cannot be used quantum-mechanically consistently for any two nucleons

Throwing ***a nucleon's*** momentum from one single nucleon momentum distribution is fine…

- But, what do we throw ***the second nucleon*** from?
- Two body nucleon-nucleon momentum distributions a la Wiringa?
  - Assumptions of this theoretical work may not be self-consistent with $n \rightarrow \bar{n}$ due to increase in potential from correlated pairs of nucleons using the AV18+UX potential, but further investigation on my part will continue
  - **Must currently be *extrapolated* to $^{40}_{18}Ar$** (how?)

Throwing two nucleons from a single nucleon non-local Fermi gas momentum distribution does not preserve the correlations between the lower momenta of nucleons at the surface of the nucleus

- Thus, implementation of a corrected annihilation distribution *could* lead to non-trivial, non-spherical, low-momentum signal topologies
- *Could* make the charged pions produced effectively invisible to even low-threshold detectors like DUNE

Suggested Enhancements to Current Physics Simulations (cont.)

3. A larger number of branching channels are known (see our recent publication)

Using $\bar{p}p$ and $\bar{p}d$ data, $SU(3)$ symmetry and isotopic relations, more than ~ 100 channels are actually possible

- Meson resonances could lead to nontrivial final state topologies

4. A full intranuclear cascade would be nice to include to study differences with these proposed updates

Deliverables

1. Implementation of small edits to the NNBarOscillationPrimaryVtxGenerator.cxx which take into account the proper radial annihilation position distribution, as calculated by Jean-Marc Richard. This will be sourced and thrown randomly from a numerically defined 1D histogram.
   - This is currently only useful for intranuclear neutron-antineutron transformation in Argon, and while it is entirely impractical to request that Jean-Marc calculate such distributions for all nuclei, in principle these distributions already exist for the only historically used targets for these experiments: the deuteron, oxygen, and iron
   - See, for instance, E. Friedman and A. Gal, Phys. Rev. D 78, 016002
   - Thus, similarly, they could each be implemented within the NNBarOscillationPrimaryVtxGenerator.cxx and read in identically depending upon what value of A (number of nucleons) is called

2. Switching to (at least) a local Fermi gas model.
   - This will hopefully preserve the correlation between low Fermi momenta and high radii at the surface of the nucleus (where the transformation and annihilation are more likely to take place due to a lack of binding energy), but I need to investigate how this is implemented within GENIE currently
   - Ideally, I would like to cycle through many or all of the nuclear models internal to GENIE with their various definitions of the momentum distribution and see what effects these create on the observable final state in DUNE

3. Switching to Intranuke hN and compare to Intranuke hA with these changes.

Possible Deliverables

1. Once I *understand* them properly, *possibly* integrate two-body momentum distributions (a la Wiringa) into GENIE to avoid quantum mechanical issues with throwing two nucleons from just one single nucleon momentum distribution
2. *Possibly* change the annihilation channels and associated branching ratios to be more consistent with my colleagues' own experimental and theoretical models for these kinds of annihilations (see tables within https://arxiv.org/abs/1804.10270)

Milestones and Code Location

B. Milestones are expected to track rather quickly, as I do not plan to reinvent what Jeremy Hewes has already done so well. All that needs to be changed are a few of the aforementioned physics assumptions.
   - I expect to be done with *simulation enhancements* **quite soon**, and some personal *validation testing* of these changes by June 2019

C. With Steven Gardiner, I've been able to place my modified code is available under "new_nnbar" Generator git branch, and I will keep all of my changes entirely separate from any other current GENIE development
   - All that I did was copy the original code to this repository and play with it separately there

Questions?

<u>Accurate Simulation of Atmospheric Neutrino Background and Nucleon Decay Events in DUNE</u>

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 understanding the baryon (B) asymmetry of the universe (BAU) and the ultimate stability of matter itself. These two are possibly inextricably linked through beyond SM (BSM) B and $B - L$ number violating processes, a key requirement of the Sakharov conditions, the renormalizability of the SM, and *post-sphaleron baryogenesis* [1,2]. Future high-energy experiments could potentially test such theories, opening the prospect of discovering the mechanism behind the BAU. I propose to undertake a *comprehensive and authoritative* Monte Carlo (MC) study to assess the BSM search potential of the forthcoming Deep Underground Neutrino Experiment (DUNE) in its quest to directly and indisputably observe the BSM physics theoretically responsible for this symmetry violating mechanism in the early universe.

Such $B - L$ violating BSM processes generally fall under nucleon decay (NDK) searches, among them neutron-antineutron transformation ($n \to \bar{n}$) [2,3] and *arguably* proton decay (PDK). The primary searches for these 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 (WC) detector of Super-Kamiokande (SK) [4], 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 $1.9 \times 10^{32}\ yr$; when converted into a free mean $n \to \bar{n}$ time through the *conventional* theoretical nuclear physics formalism [3], this lower limit becomes $2.7 \times 10^{8} s \approx 8.5 yr$. This value can be contrasted with the predictions for the free mean $n \to \bar{n}$ time in [2], making it clear that a new landmark, sea-changing experiment(s) is necessary to further explore the pertinent parameter space for these phenomena.

Enter DUNE, 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 $n \to \bar{n}$ and PDK 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, or the three-track topology of a "golden channel" PDK ($p \to K^{+}\nu \to \mu^{+} \cdots \to e^{+} \cdots$) event. Also, upon noting the possibility of detecting and reconstructing $\gtrsim 25\ MeV$ kinetic energy protons in LArTPCs, 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 $\gtrsim 10^{35} yr$ 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 [5] collectively limit this reach by as much as nearly two orders of magnitude, hoping to better existing experimental limits [4] by a mere factor of five. This effectively disallows an *actual* discovery.

My *own* work and *burgeoning* expertise on the topic of intranuclear $n \rightarrow \bar{n}$ has been recognized by the DUNE collaboration's Nucleon Decay and High-Energy Physics (NDKHEP) Working Group, where I have recently become the resident specialist. My $n \rightarrow \bar{n}$ analyses have produced promising results when contrasting signal with ν_{atm} background in MC, suggesting improvements could be made to [5] 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) [5] analysis forgoes such particle identification and utilizes only partial reconstruction; this creates a 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 myself and colleagues that potentially first-order physics has been overlooked in the modeling of signal and background in [5]. For instance, because the $\bar{n}$ annihilation model used within GENIE 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 affected; to state this explicitly, $n \rightarrow \bar{n}$ is likely to occur at the surface of the nucleus [6], 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 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.

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. It is because of these needs that I am seeking the Science Graduate Student Research (SCGSR) Program Fellowship to complete future work in the Department of Energy's research priority of *Theoretical and Computational Research in High Energy Physics*. The focus of this effort will be to *study and improve* MC simulations of ν_{atm} and BSM NDK processes. These will be used in an authoritative feasibility analysis of *potential* experimental lower limit extensions within the LArTPC modules of the future DUNE. Specifically, under the guidance of experimentalists and theorists alike, I propose to work at Fermilab on the following three important, well-related tasks for the DUNE collaboration and its NDKHEP Working Group:

1. In continuation of similar efforts discussed in [7], the simulation of new, reliable, ν_{atm} background samples within the DUNE ten kiloton LArTPC detector modules utilizing cross sections for electron and ν scattering developed at LANL/ANL from ab-initio quantum Monte Carlo calculations. I will implement the calculated electromagnetic cross sections for ${}^{4}_{2}He$ and ${}^{12}_{6}C$ in 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 and the Wroclaw Neutrino Event Generator (NuWro). *(6 months)*

2. The integration of these specifically designed ν_{atm} event samples into highly-developed, already constructed CNN [5] and multivariate boosted decision tree (TMVA) data analysis modules for feasibility studies of intranuclear $n \to \bar{n}$ and PDK, to be followed by an integrated analysis across these samples, allowing for an assessment of model uncertainties. *(2 months)*

3. The utilization of GENIE, GiBUU, NuWro, and other generators for an updated, improved, *more accurate* simulation of $n \to \bar{n}$ events to properly assess the possibility of reducing ν_{atm} rates to zero, fully enabling DUNE's BSM physics discovery potential. *(4 months)*

My thesis, "Towards Neutron Transformation Searches", which I have been developing the underlying physics arguments and machinery for at the University of Tennessee for nearly two years, is to be principally focused on the study of $n \to \bar{n}$ in DUNE. In particular, the sections dedicated to $n \to \bar{n}$ will detail 1) the MC generation of ν_{atm} background with new and updated generators employing updated cross sections, nucleon momentum distributions, and novel nuclear transport techniques; 2) an updated BSM physics model design for MC signal event generation including the previously discussed prevalence of intranuclear $n \to \bar{n}$ at the surface of nuclei; 3) the actual computation of MC generated BSM signal events using DUNE computational resources; 4) a full data analysis of background and signal MC generated data using NDKHEP Working Group CNN and TMVA analysis modules; and finally 5) an assessment of simulation uncertainties by comparing outputted analysis module scores across multiple generators for signals and backgrounds. All this work, along with separate future experimental work at my home institution, will propel me toward the defense of my doctoral dissertation by December 2020.

Since model and meson cross section uncertainties form a dominant and convoluted systematic in limiting DUNE's reach to search for BSM processes such as $n \to \bar{n}$, it is important that I assess these by comparing many independently developed generators to understand the broad consistency of various theoretical nuclear models within those event generators, *or lack thereof*. Evaluation of whether the discovery potentials of DUNE are indeed independent across these variations will be an authoritative demonstration of DUNE's BSM search capabilities. Together, all the previously mentioned nontrivial dependencies merit further, in depth studies to ascertain DUNE's true potential experimental reach. The model development, implementation, and simulation work proposed here has the possibility to broadly impact future BSM searches in DUNE, principally including NDK processes like $n \to \bar{n}$ and PDK. Understanding the complex interplay of these proposed phenomena with accurate ν_{atm} background simulation is key to justify the feasibility of such BSM searches. Results obtained from all the projects listed in this research proposal will impact the technical design of DUNE, will be published in future technical design reports, and I would similarly expect some technical publications for the ν, baryon number violation, BSM, and DUNE communities to be produced from this work over the next two years.

References:

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[4] K. Abe et al, Physical Review D **91**, (2015).
[5] J. E. T. Hewes, thesis, Faculty of Science and Engineering, University of Manchester, 2017.
[6] J.-M. Richard, C. Dover, and A. Gal, (Oak Ridge, TN, 1996).
[7] S. Pastore, 2017 FNAL Intensity Frontier Fellowship Program.

Overview of Issues with Current Neutron-Antineutron Oscillation GENIE Generator

Review written by Joshua Barrow

Generator originally created by Jeremy Hewes and Georgia Karagiorgi

January 2019

A short note to the reader

The current iteration of the GENIE NNBarOscillation event generator was created by Jeremy Hewes and Georgia Karagiorgi in late 2016/early 2017.

Neutron-antineutron transformation is a process that DUNE may have a chance to *discover* if proper background rejection is achieved, making possible a revolutionary impact on physicists' understandings of several popular baryogenesis models. If definitively observed, it will foster a significant step toward an understanding of the matter-antimatter asymmetry of the universe. Given these possibilities, it is important that one takes care to understand the assumptions of the simulations for both signals and backgrounds, and to make each as accurate as possible. My first task is to update the signal generator for this purpose.

I have begun the process of going through the GENIE-v3 NNBarOscillation module (if anything, as a learning exercise), and this is my working Mathematica Notebook to keep track of progress and discuss things with myself. All the code that I have extensively commented and edited can be found (publicly) on my drive on FNAL's geniegpvm01 machine under "/genie/app/users/jbarrow/genie-v3/Generator/src/-Physics/NEW_NNBarOscillation".

An overview of the first few classes of "NNBarOscPrimaryVtxGenerator.cxx", particularly "NNBarOscPrimaryVtxGenerator::GenerateOscillatingNeutronPosition"

The part of the NNBarOscillation module (accessible via my GENIE-v3 build under "Generator/src/Physics/NNBarOscillation") that I have been investigating chiefly is the

“NNBarOscPrimaryVtxGenerator.cxx” routine, a C++ script that, from what I can tell, does *most all* of the heavy lifting when it comes to the actual nitty-gritty details of the simulation. Within this routine, I can see that Jeremy wrote this generator with generality in mind, which is entirely laudable, though I feel there are *some* issues with the level of generality that he pursued.

The first parts of the script is perfectly fine, wherein he initializes the nucleus, two nucleons (a neutron and a general nucleon, which will eventually annihilate according to integrated branching ratios in the “...Utils...” code), and the nuclear remnant (Ar – 39 or Cl – 38) for the purposes of the event record, defining all of their mother/daughter qualities and four-momentum and space-time positions.

Following this, however, because of the wish for the generator to be useful across all nuclei, he then employs a rough approximation to calculate the nuclear radius within “NNBarOscPrimaryVtxGenerator::GenerateOscillatingNeutronPosition”. Most of us are comfortable with the nuclear radius as being dependent upon the cube root of the number of nucleons (essentially the nuclear volume). However, this is a crude approximation that does not properly take the structure of individual nuclei into account. Secondarily, presence of NN-correlations are known to reduce the nuclear radius. The first thing that goes wrong is the incorrect value of R_0 was used (it should be 1.25 fm, not 1.3 fm):

$$R = R0\, A^{1/3} \;/.\; \{R0 \to 1.25,\; A \to 40\}$$

4.27494

However, the even bigger issue is that this does not align with the known nuclear data very well at all, where, for Argon:

$$RAr = 3.4274$$

3.4274

and so leads to a rather large percent difference:

$$100\, \frac{R - RAr}{\frac{R+RAr}{2}}$$

22.0073

An overestimation of the nuclear radius could, to my mind, lead to nontrivial transport effects, perhaps de-emphasizing the presence of FSIs, but I will need to investigate the Nuclear Model further to see if this implementation is even consistent. If generality is wished for, then I think a new method using a table-like structure for all nuclei should be used; however, as our focus is argon, this is probably not necessary at this time.

Following this, he implements a nicely generalized subroutine using a Von Neumann-like method to numerically approximate and sample from the (integral of the) probability density distribution of the nucleon/neutron location/nuclear density distribution from the “Density(r,A,ring)” class built into the “Generator/src/Physics/NuclearState/NuclearUtils.cxx” script (written by Steve Dytman). It should be noted that, from what I can tell, there is no distinction between the total/effective nuclear density distribution and the neutron distribution, and so (small) surface effects for larger nuclei are not being taken into account. For Ar – 40, this method defaults to a Woods-Saxon distribution given that $A = 40$, with associated fitted constants which are themselves approximations, though not entirely bad ones.

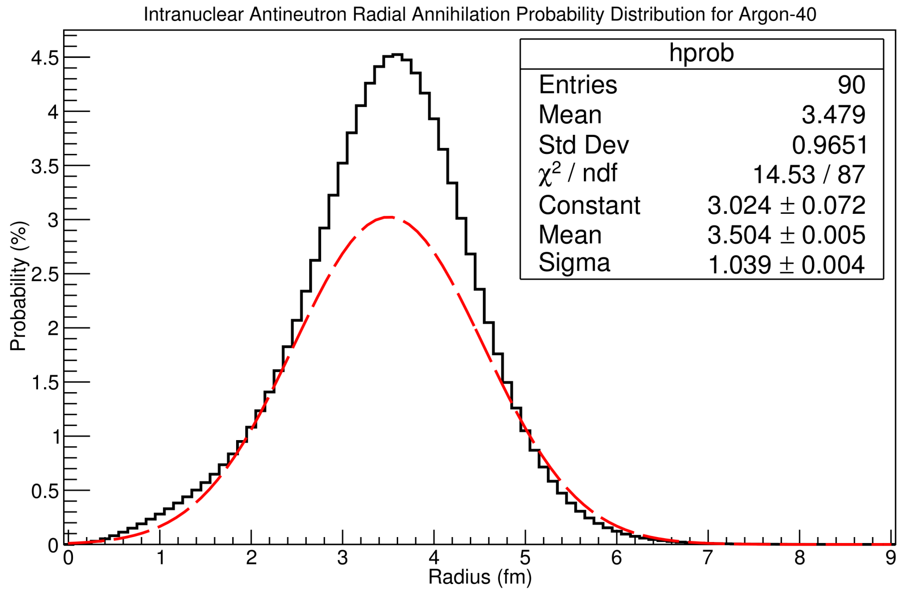
Secondarily, the actual process of the annihilation with the nearest neighbor nucleon is somewhat ill defined; in fact, what is actually done is not a *search for* a nearest neighbor to the oscillated antineutron, but an imposition that a particular nucleon *appear* right at the vertex of the oscillation (and, subsequently, the annihilation--thus, the antineutron does not actually propagate through the nuclear environment, or even have a chance to experience the change in the nuclear potential). Thus, this technique, to my mind, makes the the implementation of any kind of true nucleon-nucleon short-range correlations implausible, although a pheonomenologically-motivated recasting of the branching ratios may still be possible, or the use of pair/individual/two-nucleon momentum distributions instead. Similarly, because the annihilation partner is effectively randomly selected from *anywhere* in the nucleus, any/all correlations with nuclear position, potential and Fermi momentum *are lost* on an event-by-event basis (these are all maintained quasi-classically in the case of Elena's extranuclear neutron-antineutron transformation and annihilation on C-12 generator before undergoing a classical cascade model, see arXiv:1804.10270 for more details).

Suggestions for the "NNBarOscPrimaryVtxGenerator::GenerateOscillatingNeutronPosition" class

Here I discuss some suggestions to the "NNBarOscPrimaryVtxGenerator::GenerateOscillatingNeutronPosition" class.

I believe that the Von Neumann-like method in which the radial position is taken from the "NuclearUtils.cxx" code is no longer necessary. Given that I have a set of points of equal bin widths, I am able to define a 1D histogram and import this into the routine as a ROOT file, reading in this particular histogram, and then throwing a random number directly from this distribution. Because of this, no radial definition (as in the value of R or R_0 above) are necessary. Secondarily, it appears that, while correlations between nucleon positions and momenta are lost, the built in method of generating that the neutron/antineutron and annihilation partner have the same position is actually *good*, as the distribution provided to us by Jean-Marc Richard is in fact the *annihilation position*, not the oscillation position.

The distribution that Jean-Marc has calculated for us (and which will appear in our next publication) uses neutron binding energies, wave functions, and nucleon density functions to find the annihilation position probability, and the method will appear in our forthcoming paper together (you can also see E. Friedman and A. Gal, Phys. Rev. D 78, 016002 for a similar method). Effectively, what it implies is that the transformation can only occur when the mass difference between the two components of the neutron state vector is small, i.e., where the binding energy is low; this means that transformation will be selectively chosen on the periphery of the nucleus, implying different final state interactions after annihilation of the nearest nucleon, and different momentum distributions which must take into account their radial dependence. The full histogram of annihilation probability can be seen below:



As you can see, this distribution cannot be easily fit using a Gaussian form; I haven't tried a Lorentzian or Breit-Wigner form, but I doubt that the fit is much better (at least due to the asymmetric structure of it, though a Voigtian (relativistic Breit-Wigner) *might* be able to handle it's shape). However, overall, due to the numerical definition of this distribution, and the ease of throwing random numbers from such distributions within ROOT, I don't think we need to reinvent the wheel here--so no fitting seems necessary at all.

An overview of the "NNBarOscPrimaryVtxGenerator::GenerateFermiMomentum" class

This is an well-written and quite general method that Jeremy has made. Most "normal" things occur here: an event record is created, a "target" nucleus is selected, a "hit neutron" is selected along with its partner, and then each of them are imbued with momentum due to Fermi motion. Further, the momentum of the nuclear remnant is also calculated by subtraction of the two nucleon's momenta. Also, the removal energy of the nucleons are taken into account and properly subtracted from the four momenta of each particle in the event record. These principal nucleons' momenta and removal energy (the constituents of their four-momenta) are taken from the nuclear model being called (namely, currently a Bodek-Ritchie momentum distribution with a high-momentum, phenomenological, "short-range correlation" tail). In principle, as I understand this, there are several nuclear models which can be called to draw these momenta from, and they can simply be switched out one for the other. Thus, I should be able to relatively easily run events changing this as a parameter and see what the effect are (if any).

Suggestions for the "NNBarOscPrimaryVtxGenerator::GenerateFermiMomentum" class

The only improvements that I can conceive of are, in order of complexity, the following: 1) implement a different nuclear model (such as those using a meson-exchange current, spectral functions, etc.) and see what if any of the effects happen to be (I think that this should be fairly simple); 2) implement *two* nuclear models, or at least, call momenta from *two different* momentum distributions--this should be done due to the inherent quantum mechanical inconsistency of drawing two nucleon's momenta from just one single nucleon momentum distribution, but technically this would require knowledge of a distribution of distributions (the probability of one nucleon's momentum having a correlated relationship with the next nucleon chosen), and I need to investigate this further with colleagues before saying anything too definitive; 3) attempt to maintain some form of correlation between the momentum and the radius of the annihilating nucleons, at the very least to keep track of the utter *lack* of momentum at the surface of the nucleus, where the majority of oscillation/annihilation events occur.

An overview of the "NNBarOscPrimaryVtxGenerator::GenerateDecayProducts" class

Due so phase space calculations, this is one of the most complex subroutines of the code, and so I will not go into too much detail here. From what I can tell, it is quite generalizable, and includes an algorithm which checks the total phase space available against the rest mass of the decay constituents, switching when necessary (this is actually rather complex, and means that the *effective* branching ratios used by Super-Kamiokande sourced for this study, which no longer seem well motivated to me due to these issues, are actually *changed* within this model).

Suggestions for the "NNBarOscPrimaryVtxGenerator::GenerateDecayProducts" class

It is known from our paper on $C-12$ for the ESS NNBar collaboration (arXiv:1804.10270) that there are $\sim$100 possible channels that can occur with $\overline{n}$ and $\overline{p}$ channels on free nucleons; of course, many of these *end up* in effectively the same final state, though their overall kinematics can differ. If possible, I would like to, over time, study the insertion of these channel's branching fractions into this model for a more direct comparison with our independent generator, though some of this complexity may be lost due to the lack of (apparent Breit-Wigner) decay-width simulation within GENIE.