Free Neutron-antineutron Transformation Searches at the European Spallation Source's Large Beamport

For the NNBAR Collaboration, and Colleagues

Opportunities for Baryon Number Violating Searches to Understand Potential Mechanisms of Baryogenesis with the NNBAR Experiment

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Suggested Snowmass Topical Groups:

- (RF4) Rare Processes and Precision Frontier: Baryon and Lepton Number Violating Processes

Abstract

Baryon number violation is one of the three Sakharov conditions required for understanding baryogenesis. Searches for baryon number violation are thus of great interest to the fundamental high-energy and nuclear physics communities. With deep ties to the US particle and neutron physics community, the international NNBAR Collaboration aims to provide the broader community with world-leading sensitivities to neutron-antineutron transformations ($n \to \bar{n}$) using free ns at the forthcoming European Spallation Source's (ESS). The ESS will become the world's most powerful pulsed cold n source, and the already constructed Large Beamport will enable clean, high flux searches for $n \to \bar{n}$ with a high angular acceptance and potentially well constrained backgrounds due to the time-dependency of the long cold n pulses. With modern detector technologies and updated reconstruction techniques, NNBAR promises to be an unambiguous experiment exploring underappreciated segments of particle physics, potentially enabling the discovery of testable mechanisms of baryogenesis by achieving $\gtrsim 1000\times$ gain in $n \to \bar{n}$ sensitivity when compared to the classic experiment at the Institut Laue-Langevin. The program of research is incredibly cross-disciplinary, including but not limited to the involvement of experts in neutronics, detectors, and magnetics, creating highly dynamic collaboration across fields. The opportunity for such a a leap in sensitivity for tests of a global symmetry is rare and should not be squandered.

The observation of baryon number violation (BNV) in a laboratory experiment would be a discovery of fundamental importance to particle and nuclear physics. Within the Standard Model (SM), baryon number, $\mathcal{B}$, is a good global symmetry for experimental tests up to the TeV scale. However, BNV is anticipated: non-perturbative instanton effects in the $SU(2) \times U(1)$ sector of the SM break $\mathcal{B}$ and total lepton number, $\mathcal{L}$, while conserving $\mathcal{B} - \mathcal{L}$[1]. Although these effects are negligible at temperatures which are low compared with the electroweak scale of $\mathcal{O}(100)$ GeV, they gain dynamic importance via sphaleron processes in the early universe at temperatures of this order[2;3]. Furthermore, precision tests of the Equivalence Principle[4–6] offer no evidence for a long-range force coupled to $\mathcal{B}$, a key requirement for any hypothetical local gauge symmetry *forbidding* BNV. Most compellingly, according to Sakharov's conditions[7], BNV is required to understand the matter-antimatter asymmetry of the universe. Processes which violate $\mathcal{B}$ by two units ($\Delta\mathcal{B} = 2$) such as dinucleon decays and neutron-antineutron oscillations or transformations, $n \to \bar{n}$[8–16], offer unique and comparatively unexplored discovery windows onto BNV. Some early studies of $n \to \bar{n}$ include[9;11–15;17], and a recent review is found in[10]. n conversion processes, at potentially observable rates, are anticipated in scenarios of baryogenesis and dark matter[17–22], supersymmetry[23;24], extra dimensions[25–27], cosmic rays[28;29], neutrino mass generation mechanisms[9;17;20;21;30;31], extensions of the Standard Model with certain types of scalar fields[32;33], and even in oscillations of (anti)atomic matter[34;35]. This Letter of Interest concerns a remarkable opportunity, made possible by the construction of the European Spallation Source (ESS), to search for neutron conversions with the HIBEAM/NNBAR experiment[10;36] with an ultimate sensitivity improvement more than three orders of magnitude better than the previous search[37].

For any $n \to \bar{n}$ experiment, one must maximize the figure of merit, $\langle Nt^2 \rangle$, encapsulating the need for the maximum number of ns on target over the tenure of the experiment, N, and observing those ns on their respective flight paths for a maximum amount of time, t[10;36]; the probability of a conversion is expected to grow as t^2 in the quasi-field-free limit[10;38;39]. Together, these allow an experiment to uncover the minimum $n \to \bar{n}$ oscillation period, $\tau_{n\bar{n}}$. By maximizing flux, angular acceptance, background rejection, flight path length, and utilizing modern detector and reconstruction technologies, the proposed NNBAR program[10;36] at the European Spallation Source (ESS) is able to culminate in an ultimate sensitivity increase for $n \to \bar{n}$ of three orders of magnitude ($\gtrsim 1000\times$)[40;41] over that previously attained with free ns after the classic search at the Institut Laue-Langevin (ILL)[37] which achieved $\langle Nt^2 \rangle = 1.5 \times 10^9 n\mathrm{s}^2$ and a lower limit on $\tau_{n\bar{n}} \geq 0.86 \times 10^8$ s. Taken together, the HIBEAM/NNBAR program[36] will enable the characterisation of a mixing sector involving ns, $\bar{n}$s, and potentially sterile neutrons, n'.

Thermal and cold ns are used as a tool throughout a wide range of scientific disciplines to provide insight into phenomena unreachable by other means, typically those utilizing photons or charged particles. The unique benefits provided by ns are reflected by the significant investments made in accelerator based n sources since the beginning of this century, of which the ESS is but the latest example. The ESS, located in Lund, Sweden, is a multi-disciplinary international laboratory which will operate the world's most powerful pulsed n source. The development of the facility has been driven by the n scattering community, and the first 15 instruments are currently under construction. The start of the User Program is expected to begin in 2023, and the 15 current instruments represent only a subset of the full 22-instrument-suite required to fully realize the ESS' scientific mission as defined in the ESS statutes. During the preceding era, n facilities' contributions to particle physics have been limited to only a handful of experimental endeavors. In light of this, regarding later-built ESS instruments 16-22, an ESS-lead analysis of the facility's scientific diversity has identified the need of a fundamental physics beamline, ANNI[42]/HIBEAM[36], as *the highest priority*. Beginning in the early-mid 2020's, and without the necessity of utilizing the expected full beam power of 5 MW available $\gtrsim$ 2030, the HIBEAM[36] program could utilize the fundamental physics beamline to consider dark sector-oriented searches through sterile n' conversions[17–22;43–45] using magnetic field controls to permit n disappearance ($n \to n'$) and n regeneration ($n \to n' \to n$), as well as cobaryogenesis-oriented searches via $n \to n' \to \bar{n}$, and possibly a small-scale $n \to \bar{n}$ search. At full power, ANNI[42] can be utilized for other beyond Standard Model physics searches such as those for n electric dipole moments.

In addition to the ANNI[42]/HIBEAM[36] fundamental physics beamline, another remarkable opportunity for the particle physics community is offered by the already constructed Large Beam Port (LBM), which in fact lies within the ESS monolith, a critical provision created specifically for the NNBAR experiment. A normal ESS beamport would be far too small for NNBAR to reach its ambitious sensitivity goals. Therefore, part of the beam extraction system in the ESS monolith has been engineered to enable the construction of a large frame covering the size of *three* standard beamports. Initially, the frame will be filled by three modularized regular-size beamports which can later be removed to provide NNBAR full access to the LBP for the duration of the experiment. It cannot be understated how such a configuration is entirely unique among currently operating n facilities. The monolith interface, supporting an opening up to 1 m^2, provides a substantial view of the voluminous cryogenic moderator with a time-averaged brilliance rivaling those of modern research reactors. The ESS as constructed enables the use of two moderators to cool ns as they propagate to their beamlines, with an upper moderator above the spallation target made available immediately upon commissioning and plans to install a lower moderator of opportunity below the spallation target in a future upgrade before $\sim$ 2030. To further develop the plans for this future upgrade to ESS capabilities, and to greatly empower NNBAR, a design study[41] will begin fashioning a new lower moderator consisting of liquid deuterium and able to provide a high-flux of cold ns to benefit both NNBAR and future n scattering experiments. This project, termed HighNESS, is funded by the Research and Innovation Action within the EU's Horizon 2020 program for €3M over the next three years. The evaluation letter

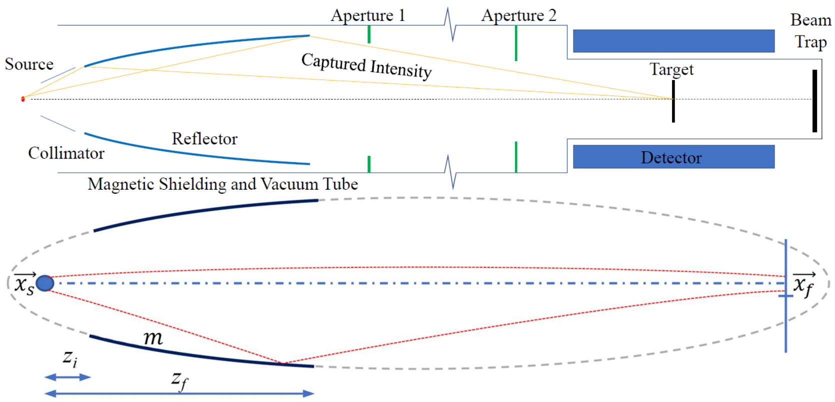

Figure 1: Top: A schematic overview of the baseline 200-300 m long NNBAR experiment, where the LBP source is shone onto a thin ^{12}C[47;48] annihilation foil downrange before entering a beamstop; the ^{12}C annihilation foil is the current baseline due to the low (high) n ($\bar{n}$) cross section, though others, including ^{9}Be, are under investigation. The pseudoellipsoidal reflector enables the maximization of the figure of merit. Bottom: A simplified view of potential n trajectories with and without reflection from the n supermirror; ignoring beam anisotropies, gravity, and divergence, the reflector would be a perfect ellipsoidal section. However, taking these effects into account requires detailed parametric optimization of many inputs (including but not limited to those shown) using a *differential* reflector[36;54]. The differentiable shape creates a pseudoellipsoid, permitting precise design, sensitivity maximization, and construction for the NNBAR experiment.

from the European Commission unambiguously highlighted the importance of "the potential for discoveries in the new Physics beyond the standard model" through the NNBAR experiment. A key deliverable of the HighNESS project is the Conceptual Design Report of NNBAR, of which the Collaboration's recent white paper[36] is an important first step.

Achieving maximum $\langle Nt^2 \rangle$ at NNBAR will utilize several key improvements to n scattering and high-energy particle detectors made over the last 30 years since the original ILL experiment[37]. Beyond advancements in detector materials, timing, and software reconstruction capabilities related to identifying[46] topologically spherical "π-star" $\bar{n}$ annihilation events[47–49] on a thin ^{12}C foil surrounded by detector elements, of critical importance is the growing capabilities of advanced, high m-valued[50–53] n reflectors to guide ns downrange into an intense, well constrained focus. An effective reflector must be fully illuminated by the source; thus, a substantial amount of the overall n beam intensity will have trajectories which deviate significantly from the nominal beam trajectory axis. To achieve this, reflecting angles for even fairly cold ns ($\sim$1000 m/s) will exceed that of the limit of the best traditional reflectors. NNBAR will thus utilize high m-valued n *supermirror* technologies[50] which have been successful as a means to guide thermal and cold ns to many scattering instruments at both pulsed and continuous n sources. NNBAR will utilize the same multi-layered surface coating treatment on its reflector to gather and focus the wide range of n trajectories incident from the source. To do so, NNBAR requires reflectors with a surface reflectivity of $m \gtrsim 6$, i.e. a reflection capability six times higher than that of polished nickel. As shown at the top of Figs. 1, ns emerging from the LBP are reflected via a pseudoellipsoidal, differential supermirror along a magnetically shielded volume towards a ^{12}C target foil, surrounded by an annihilation detector; a beam trap downrange absorbs the beam. The detection efficiency of an annihilation event on the foil is assumed to be $\gtrsim 50\%$ as in the ILL experiment[37]; work is underway to assess whether such detection is also expected to be backgroundless, as before[37]. The bottom of Figs. 1 also shows a sketch of a differential reflector configuration with some parameters which can be optimised to maximise the sensitivity of the NNBAR experiment, including the source focal point position, $\overrightarrow{x_s}$, the target focal point, $\overrightarrow{x_f}$, the reflector start, z_i, and the reflector end, z_f[36].

Assuming an experimental duration of three years, these improvements collectively provide an enhancement in the $\langle Nt^2 \rangle$ figure of merit by $\gtrsim 1000\times$ILL using *only* a lower moderator, enabling an increase in $\tau_{n\bar{n}}$ by $\gtrsim 30\times$ILL. The increases in sensitivity can be broadly decomposed into the gain factors given in Table 1, with sensitivity increases due to the greater source intensity, propagation length, and run time, though the largest gain is from the use of now commercially available high-m reflectors.

A full quantification of the NNBAR sensitivity is part of the HighNESS program. However, it should be noted that, in principle, running times can be extended to mitigate against any loss of sensitivity. Furthermore, estimates provided in[36;54] are rather conservative with an assumed selection efficiency for an annihilation event of $\sim 50\%$ as obtained at the ILL; indeed, detector technology and data analysis methods in experimental particle physics are now substantially more advanced, and so a far higher efficiency could be expected. These, together with the opportunity to view *both* the upper and lower moderators, provide ample ability to mitigate any unexpected losses in sensitivity.

Here, we have discussed the ongoing progress of the future NNBAR experiment, of which a small-scale ORNL set of experiments[45;55–58], the HighNESS[41] project, and HIBEAM program[36] are critical first steps. We invite the community to support and join in this monumental cross-disciplinary effort to discover the nature of BNV, potentially uncovering the mechanism of baryogenesis.

Table 1: Breakdown of gain factors for NNBAR with respect to the last search for free $n \to \bar{n}$ at the ILL[37] when viewing the ESS LBP and using a lower liquid deuterium moderator only.

Factor	**Gain wrt ILL**
Source Intensity	≥ 2
n Reflector	40
Length	5
Run time	3
Total gain	≥ 1000

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