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The HighNESS Project and Future Searches for Neutron Oscillations with Free Neutrons at the European Spallation Source

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The European Spallation Source, presently under construction in Lund, Sweden, is a multi-disciplinary international laboratory. It will operate the world's most powerful pulsed neutron source. Taking advantage of the unique potential of the ESS, the HIBEAM/NNBAR collaboration has proposed a two-stage program of experiments to perform high precision searches for neutron conversion in a range of baryon number violation (BNV) channels culminating in an ultimate sensitivity increase $n \to \bar{n}$ oscillations of three orders of magnitude over the previously attained limit obtained at the Institut Laue-Langevin ILL. The first stage of this program HIBEAM (High Intensity Baryon Extraction and Measurement) will employ a fundamental physics beamline during the first phase of the ESS operation. This stage focuses principally on searches for neutron conversion to sterile neutrons n' that would belong to a "dark" sector. The second stage, NNBAR, will exploit a large beam port, specifically designed in the ESS target station monolith for this experiment, to deliver the maximum possible neutron flux and search directly for $n \to \bar{n}$ oscillations. Supported by a Research and Innovation Action within the EU Horizon 2020 program, a design study (HighNESS) is now underway for the design of the ESS second neutron source which will be also optimized in order to boost the performance of the NNBAR experiment.

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[*] Speaker

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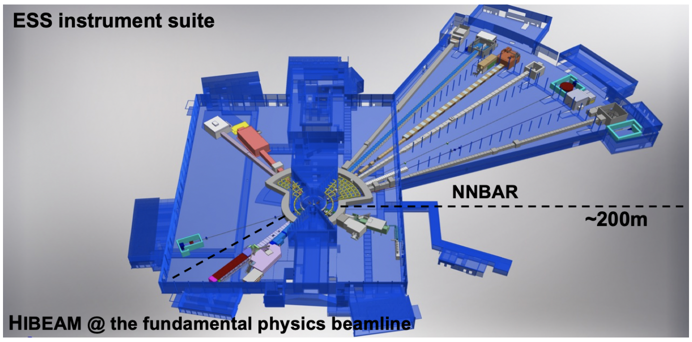

Figure 1: The ESS instruments suite and the locations for the HIBEAM and NNBAR experiments.

1. Introduction

The European Spallation Source (ESS) [1] currently under construction in Lund in southern Sweden will be the world's most powerful facility for research using neutrons. The ESS, organized as a European Research Infrastructure Consortium, is an international laboratory with host countries Sweden and Denmark and eleven partner countries. The project has been driven by the neutron-scattering community and the construction budget includes 15 instruments covering a wide range of topics in neutron science. In addition to neutron scattering the higher intensity and the pulse structure of ESS provide remarkable possibilities for fundamental physics research. In this context, the HIBEAM/NNBAR collaboration has proposed a program at the ESS [2] that addresses topical open questions such as the origin of the matter-antimatter asymmetry and the nature of the dark matter and is sensitive to the scale of new physics in excess of those currently available at colliders. In figure 1 the ESS instrument suite is shown with the location of HIBEAM and NNBAR experiments. HIBEAM will make use of the fundamental physics beamline (ANNI [3]) while NNBAR will have a dedicated beamline that will exploit a Large Beam Port (LBP) a unique feature of the ESS facility. In the ESS monolith, a 3.5 steel wall surrounding the target, a part of the beam extraction system has been engineered such that a large frame covering the size of three standard beamports has been constructed. Since this beamport is considerably larger than the ESS standard beam port it is referred as the Large Beam Port. Initially, the frame will be filled by three regular-size beamports which will be later removed to provide the LBP to NNBAR throughout the planned three year duration of the experiment, and eventually replaced at its conclusion.

2. Scientific Motivations

One of the major longstanding open questions in modern physics is the origin of the matter-antimatter asymmetry of the universe or baryogenesis [4]. A key ingredient for baryogenesis is so-called baryon number violation (BNV) one of the three basic conditions proposed by Sakharov needed to explain the observed asymmetry. A further open question concerns the nature of the dark matter [5]. Motivated by many astrophysical observations, such as galactic rotation curves, a form of matter is thought to exist which does not interact with the electromagnetic field and which has affected the structure and evolution of the universe. However, like the matter-antimatter asymmetry, dark matter remains poorly understood.
To address these two issues the HIBEAM/NNBAR collaboration proposed a two-stage program

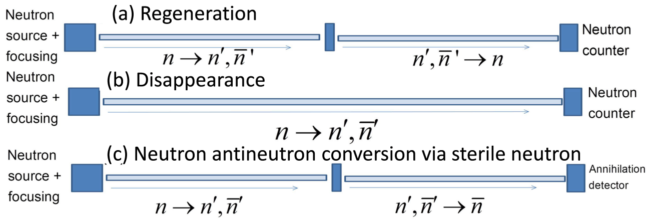

Figure 2: Illustration of the neutron to sterile neutron transitions to be sough in the HIBEAM experiment: (a) regeneration, (b) disappearance, and (c) neutron-antineutron transition via a sterile neutron state. Modes (a) and (c) require a neutron absorber to be placed at the halfway point of the beamline.

where HIBEAM will focus on the search for baryon-number-violating process due to sterile neutron transitions and conduct a pilot neutron-antineutron search in preparation for a high precision search with NNBAR. The sterile neutron states sought by HIBEAM can belong to a “dark", sterile sector of particles [6] that can feebly interact via mixing with a neutron[1], as well as interacting gravitationally. Sterile neutron states can also address a long-standing anomaly between measurements of the neutron lifetime made with neutrons in flight and trapped neutrons [6]. An overview of the proposed searches can be seen in Figure 2: three possible mechanism will be studied at HIBEAM: neutron regeneration ($n \longrightarrow [n', \bar{n}'] \longrightarrow n$), neutron disappearance ($n \longrightarrow n'$) and neutron-antineutron conversion via regeneration from a sterile neutron state ($n \longrightarrow [n', \bar{n}'] \longrightarrow \bar{n}$). All these searches will be performed scanning the magnetic field in the range from -500 mG to 500 mG since the transition could be enhanced or suppressed depending on the value of the magnetic field the neutron experience [2]. The improvement in sensitivity for these channels compared to previous work will be: up to one order of magnitude for the disappearance mode, while for the regeneration and neutron-antineutron transition via a sterile neutron state there are no previous limits.

The second stage of the program, NNBAR, will search for the direct process $n \longrightarrow \bar{n}$ with an ultimately expected sensitivity three orders of magnitude greater than the previous free-neutron search at the Institut Laue-Langevin (ILL) [7]. The sensitivity increase comes from: higher source intensity, propagation length and run time, detector developments, and large improvements in reflector technology in the last three decades since the previous experiment. The observation of such a transition $n \longrightarrow \bar{n}$ will demonstrate that baryon number (B) is not conserved and therefore matter containing neutrons is unstable. It will also provide a clue as to how matter in our universe might have evolved from the B = 0 early universe, and address the origin of the observed matter-antimatter asymmetry of the universe. A null result at the anticipated sensitivity would correspond to a lower limit on the matter-instability lifetime of about 10^{35} years. Combined with data from the Large Hadron Collider and other searches for rare processes it would severely constrain the possibility of any baryogenesis below the electroweak phase transition involving first-generation quarks, one of the few experimentally-testable ideas for baryogenesis.

3. The HighNESS project

Among the many factors responsible for the sensitivity improvement of the NNBAR experiment there is a stronger neutron source. To design the future ESS source a project termed HighNESS

[1]Like the photon and neutrinos, neutrons are one of the few particles that can be copiously produced at high intensity and studied as candidate portals to a sterile “dark" sector. This is because the neutron is electrically neutral and long-lived.

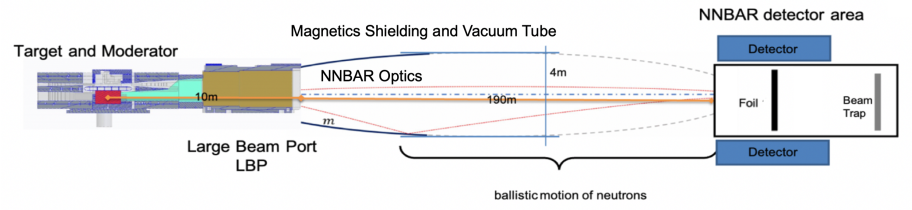

Figure 3: Sketch of the NNBAR experiment (not in scale). The experiment starts with the source, then a beam extraction system made by optical components reflect and focus the neutrons to the annihilation target, where, if a neutron to antineutron oscillations have occured, the antineutron will annihilate in the target producing a multipion signals. The multipions signal will be revealed by a detector able to distinguish such signature. The neutrons will fly in a magnetic-shielded low vacuum region.

has been initiated. The project, funded by the European Framework for Research and Innovation Horizon 2020, has the scope of designing the new source that will be installed below the spallation target (see figure 4). Such high-intensity source will not only be beneficial to NNBAR but also to several condensed matter applications that will benefit from a high neutron intensity [8]. Compared to the first source, located above the spallation target and designed for high cold and thermal brightness, the new source will provide higher intensity, and a shift to longer wavelengths in the spectral regions of Cold (4-10 Å), Very Cold (10-40 Å), and Ultra Cold (several 100 Å)) neutrons. Part of the HighNESS project is also dedicated to the development of the instruments that will make use of the new source and will complement the initial suite of instruments already planned at ESS, for this reason, the Conceptual Design of NNBAR is also included in the project and in the next sections, the current developments on-going in the NNBAR experiment will be described.

4. Towards a conceptual design report of the NNBAR experiment

To reach the estimated sensitivity for the neutron antineutron oscillation search it is necessary to optimize all the different parts that compose the NNBAR experiment. In Figure 3 a sketch of the experimental setup is shown. From left to right: the moderator system composed of a liquid deuterium LD_2; the neutrons will be extracted throughout the large beam port where a special reflector (also under design as a part of the HighNESS project) will focus them on the annihilation target (a carbon foil), where, if a neutron to antineutron oscillations have occurred, the antineutron will annihilate in the carbon target producing a multipion signal. To avoid breaking the energy degeneracy between neutron and antineutron, and suppress the probability of oscillations, the neutrons have to fly in a magnetic-shielded low vacuum region until they reach the target [2]. A dedicated magnetic shielding system is also currently under design. Surrounding the annihilation target a detector able to reveal such signal will be installed.

4.1 The ESS high-intensity moderator and the NNBAR beam extraction system

A liquid deuterium moderator with a large emission surface providing a high flux of slow neutrons represents the current baseline and is shown in figure 4. The moderator will serve two openings: one is the NNBAR LBP and the other one is a beam port dedicated to condensed matter instruments. Two beryllium filters will be applied at the opening to increase the flux of

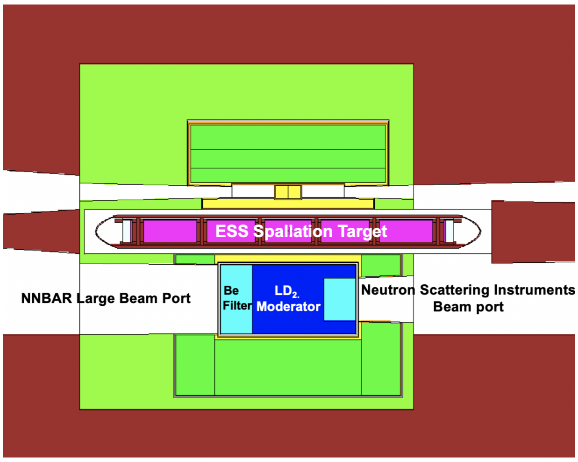

Figure 4: The ESS high-intensity source. A large liquid deuterium moderator (blue) is placed below the tungsten spallation target (pink), and is surrounded by a beryllium reflector (green). The NNBAR and the condensed matter openings are equipped with a beryllium filter (light blue) to increase the flux of neutrons above 4 Å.

neutrons above 4 Å (*i.e.* these are the neutrons that contribute more to the NNBAR figure of merit). Preliminary simulations show that this moderator can deliver an integrated neutron intensity for wavelength above 4 Å of $7\times10^{15} n/s/sr$ which represents an improvement compared to the previous design [9].
The gain comes from the large emission surface and the presence of the cold beryllium filter. It is important to point out that the source is being optimized at the same time as the design of a dedicated optics system for focusing of the extracted neutron beam. The NNBAR figure of merit is given by $\sum_i N_{ni} \cdot t_{ni}^2$ where for velocity spectrum bins i, N_{ni} is the number of neutrons per unit time reaching the annihilation detector after t_{ni} seconds of flight. Therefore the optics should be able to optimize both these parameters. The current configurations under study are elliptical nested mirrors and, as a special case of such mirror systems, a nested variant of Wolter optics.

4.2 The annihilation detector

The NNBAR detector needs to be able to reconstruct the annihilation of an antineutron with a thin carbon foil located in the detector area (see figure 3). The signature produced by this process is a multipion final state with invariant mass near 1.9 GeV [10]. To identify such signature a detector including tracking and calorimetry is being designed with the aid of Geant4 [11]. Given that the experiment is looking for an ultra-rare process, the goal is to develop a detector that is able to claim a discovery with only one event recorded. The current configuration under study is shown in figure 5 and foresees a silicon tracker to be placed inside the vacuum tube, which guarantees good vertex resolution and corrects any possible multiple scattering effects when particles travel through the vacuum tube. A time projection chamber TPC that will provide tracking and dE/dx measurements will be needed as will a stack of 10 scintillator slats for particle range measurements. An electromagnetic calorimeter made of lead glass[2] will be used to measure the photons from π^0 decay. Finally, a dedicated cosmic veto will surround the detector. .

[2]A prototype calorimeter comprising scintillators and lead-glass is under construction [12].

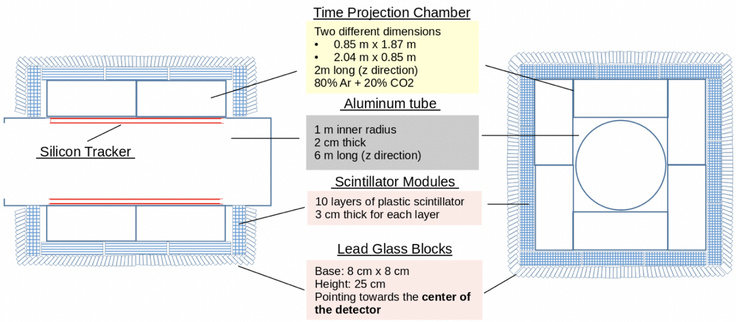

Figure 5: Overview of the NNBAR detector.

5. Conclusions

We have presented a program to search for neutron oscillations at the ESS. The program foresees a first stage dedicated to sterile neutron searches, HIBEAM, and will ultimate with the NNBAR experiment with a sensitivity of three orders of magnitude compared to the previous search. The possibilities to make such a leap in sensitivity are rare and should not be discarded.

6. Acknowledgements

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