PROCEEDINGS OF SCIENCE

Fundamental Physics with HIBEAM at the ESS

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One of the great open questions in modern physics is the origin of the matter-antimatter asymmetry. This requires baryon-number violation, which has never been experimentally observed. Baryon-number violation may arise in the neutron sector as the direct conversion between neutrons and antineutrons, or with a sterile/mirror neutron.

This process will be probed with the proposed HIBEAM/NNBAR program, a two-stage experiment at the European Spallation Source. The initial stage of the program, HIBEAM, will present opportunities to search for baryon-number violation in neutron conversion to antineutrons, or to sterile neutrons (as a disappearance search) or to sterile neutrons and into neutrons/antineutrons, with discovery potential reaching a factor of ten higher than previous experiments. HIBEAM also presents unprecedented sensitivity for direct searches for low mass axions as a dark matter candidate, surpassing previous results by two-to-three orders of magnitude for axion masses between 10^{-22} eV to 10^{-16} eV. Additionally, HIBEAM presents opportunities to search for a nonzero neutron electric charge as well as an electric dipole moment of the neutron with world-leading sensitivity.

In this talk we present the fundamental physics opportunities of HIBEAM at the European Spallation Source.

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PoS(EPS-HEP2025)433

1. Introduction

As is commonly known today, the Standard Model of particle physics omits to describe several observed phenomena. These include the matter/antimatter asymmetry, dark matter, dark energy, grand (strong+electroweak) unification, and gravity. In order for the former to arise, three conditions defined by Sakharov [1], need to be fulfilled: (1) there must be processes that violate the accidental baryon number B symmetry, (2) there must be processes that violate the C- and CP-symmetries, and (3) these interactions must take place outside of thermal equilibrium.

The first of the Sakharov conditions, requiring baryon number violation, may also be fulfilled through the violation of the lepton number L, if this can be transmitted to the baryon sector through other processes. Phenomena that violate B and/or L include grand unification models, sphaleron processes, hidden sector processes, and supersymmetry. These may present as proton decay, neutrinoless double beta decay or neutron conversion into sterile neutrons or antineutrons. With the proposed HIBEAM/NNBAR program we aim to probe the matter/antimatter asymmetry of the Universe through the search for neutron conversions [2].

2. HIBEAM at the European Spallation Source

The European Spallation Source (ESS) will be the world's highest intensity neutron source, located in Lund, Sweden, with operations starting in 2027. The ESS neutrons will be produced through the spallation process, where a 3 ms pulsed proton beam (2 GeV; initially with 2 MW, nominally with 5 MW) is incident on a rotating tungsten target wheel. The neutrons are then cooled using moderators and directed towards the 15 instruments that are decided for operation at the ESS [3]. A call is presently open to decide on additional instruments at the ESS, thus presenting an opportunity for the wide variety of fundamental physics experiments that can be performed [4].

The proposed HIBEAM instrument [5] will have sensitivity to several fundamental physics processes using neutrons, e.g. the conversion from neutron to antineutron and to sterile/dark sector neutron, and searches for ambient axion-like particles as dark matter candidates, for a non-zero neutron electric charge, and the neutron electric dipole moment. It will also be sensitive to exotic neutron decays [6]. The beamline will be 50 m long and magnetically controlled, and an optional beam stop will be placed in the middle of the beamline. At the end of the beamline there will be the detector area, where different detectors will be placed to accommodate the different science cases. See Fig. 1.

The most recent search for direct neutron-antineutron conversion was done at the Institut Laue-Langevin, ILL, neutron source, and published in 1994 [7]. This produced a lower limit on the neutron lifetime in the process as $\tau_{n\to\bar{n}} > 8.6 \times 10^{7}$ s using a neutron beam incident on an annihilation detector. In HIBEAM, the neutron-antineutron conversion will be studied by placing an annihilation detector at the end of the HIBEAM beamline, where it is essential that the 20 cm radius beamline is magnetically shielded to preserve the neutron-antineutron degeneracy. This is shown as *Experimental setup (a)* in Fig. 1. The low speed, $\sim$ 1000 m s^{-1}, will allow for a long neutron propagation time over the course of the beamline. At the end of the beamline the neutrons reach a thin carbon target foil, where any converted antineutron will annihilate with a neutron to produce a near-isotropic shower of typically 3–4 pions. The pions will then be detected, first,

PoS(EPS-HEP2025)433

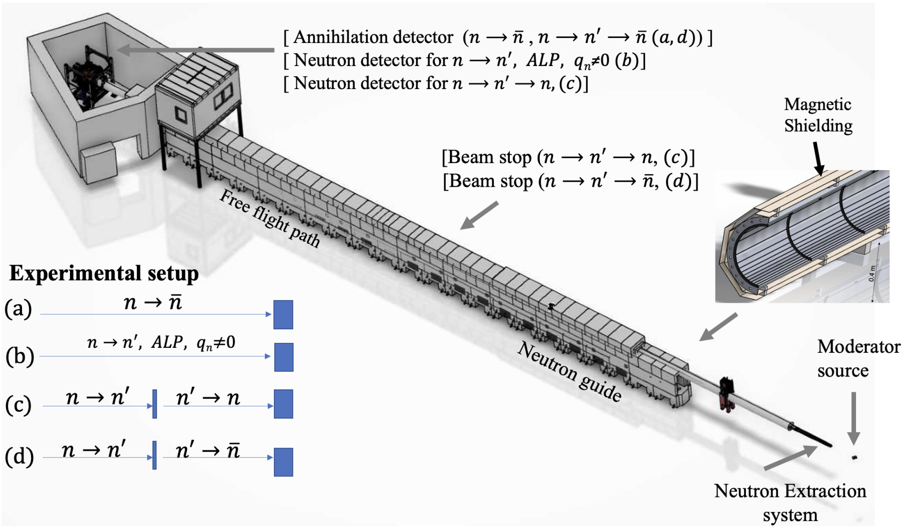

Figure 1: The HIBEAM instrument beamline [5].

using a time projection chamber, TPC, surrounding the beampipe, and, second, with the WASA crystal calorimeter [8], after which the detections will be processed with the HIBEAM data pipeline to ensure signal purity [9]. With a neutron flux of $10^{12}\,n/\mathrm{s}$ and 3–4 years of observation time, HIBEAM is expected to improve upon the previous results [7] by a factor of 10.

In addition to the neutron-antineutron conversion, HIBEAM will be sensitive to neutron conversion into sterile neutrons [5]. This conversion is dependent on a degeneracy between neutrons and sterile neutrons, which may occur at a non-zero magnetic field. Therefore, this search will be done while scanning over a magnetic field $[-2.0\,\mathrm{G}; 2.0\,\mathrm{G}]$. This will be done over three different channels:

- *Disappearance:* $n \longrightarrow n'$
  Shown as *Experimental setup (b)* in Fig. 1
- *Regeneration:* $n \longrightarrow n' \longrightarrow n$
  Shown as *Experimental setup (c)* in Fig. 1
- *Anti-regeneration:* $n \longrightarrow n' \longrightarrow \bar{n}$
  Shown as *Experimental setup (d)* in Fig. 1

The disappearance channel will be studied using a highly sensitive neutron detector that can resolve the small reduction in neutron flux that results from the conversion into sterile neutrons. The regeneration and anti-regeneration channels require a beamstop to be added halfway through the beamline, which can only be traversed by sterile neutrons, followed by a neutron or antineutron counter at the beamline end. HIBEAM is estimated to have sensitivities of $\tau_{n\to n'} \sim 97\,\mathrm{s}$ (disappearance), $\tau_{n\to n'} \sim 185\,\mathrm{s}$ (regeneration), and $\sqrt{\tau_{n\to n'}\tau_{\bar{n}\to n'}} \sim 230\,\mathrm{s}$ (anti-regeneration). As shown in Fig. 2, this represents an improvement of 1–2 orders of magnitude over previous results (see references 92–100 in [5], referenced in Sec. 5.2) for a large portion of the scanned magnetic field interval.

HIBEAM will also be sensitive to axions as a dark matter candidate [5, 10], as the axion or axion-like field would act as a pseudomagnetic field on the neutron beam in the HIBEAM

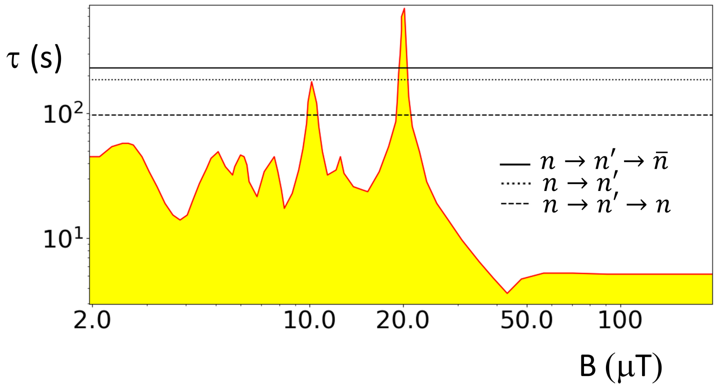

Figure 2: The HIBEAM sensitivity to $\tau_{n\to n'}$ (disappearance), $\tau_{n\to n'}$ (regeneration), and $\sqrt{\tau_{n\to n'}\tau_{\bar{n}\to n'}}$ (anti-regeneration) [5].

beamline. This would alter the Larmor frequency of the neutrons (the precession of their magnetic moment), which can be detected using Ramsey interferometry. Over the axion mass, m_a, range 10^{-22} eV $\leq m_a \leq 10^{-16}$ eV, HIBEAM would have a sensitivity that surpasses previous results (see references 101–111 in [5], referenced in Sec. 5.3) by 2–3 orders of magnitude.

Additionally, HIBEAM will be sensitive to a hypothesized very small non-zero electric charge of the neutron [5]. For this study, the neutron beam, with slightly electrically charged neutrons, will be exposed to an electric field perpendicular to the direction of travel, which would cause the neutrons to be deflected slightly (0.1 nm per 10 m of beamline, assuming a neutron charge of $q_n \sim 10^{-21}\, e$). The beam will be split near the start of the beamline, mirroring the effects on each side of the beamline. Making use of precise neutron optics, the small beam deflection can be measured at the end of the beamline by using a slit pattern. Assuming the electric charge $q_n \sim 10^{-21}\, e$, HIBEAM would reach a sensitivity improvement of a factor of 700 over previous results.

By including some or all of the equipment from the canceled nEDM@SNS project [11], the HIBEAM beamline could also be used to search for an electric dipole moment of the neutron. This would be achieved by modifying the beamline so that the neutron source is no longer in direct sight-line of the beamline. Preliminary results from dedicated ongoing studies suggest that this would yield a significant improvement over the expected results at the SNS [5].

Following HIBEAM would be the proposed NNBAR experiment to discover neutron-antineutron conversion [12]. NNBAR would consist of a 200 m long, magnetically shielded, 4 m diameter beamline situated at the ESS large beamport (with 4 times the ordinary cross-sectional area), ending at a carbon target foil to catch converted antineutrons through annihilation. Around the annihilation target would be a layered detector, with an innermost TPC, surrounded by stacked plastic scintillator staves, and covered by a lead-glass calorimeter. Overall, this results in a sensitivity improvement by a factor of 1200 over currently leading results [7].

3. Conclusions

HIBEAM is a proposed beamline at the European Spallation Source to enable several fundamental physics experiments. It would provide sensitivity to neutron-antineutron conversion surpassing current leading results by a factor of 10; enable searches for neutron-sterile neutron conversion through three different channels, resulting in sensitivity improvements by 1–2 orders of magnitude; have sensitivity to axions that would surpass current results by 2–3 orders of magnitude over the axion mass range 10^{-22} eV $\leq m_a \leq 10^{-16}$ eV; as well as improve the sensitivity to a non-zero electric charge of the neutron by a factor of 700. Preliminary results also suggest that HIBEAM would have a competitive sensitivity to the neutron electric dipole moment. Following HIBEAM would be the NNBAR experiment, improving the sensitivity to neutron-antineutron conversion by a factor of 1200.

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