The HIBEAM/NNBAR Experiment for the European Spallation Source

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Abstract

The HIBEAM/NNBAR experiment is a two stage experiment for the European Spallation Source (ESS) to search for baryon number violation. The experiment would make high sensitivity searches for baryon number violating processes: $n \to \overline{n}$ and $n \to n'$ (neutron to sterile neutron), corresponding to the selection rules in baryon number $\Delta B = 2, 1$, respectively. The experiment addresses topical open questions such as baryogenesis and dark matter, and is sensitive to a scale of new physics substantially in excess of that available at colliders. This is a cross-disciplinary experiment with a clear particle physics goal. The community encompasses physicists from large collider experiments and low energy nuclear physics experiments, together with scientists specialising in neutronics and magnetics. European, US and Asian communities are represented. The experiment would increase the sensitivity to neutron conversion probabilities by three orders of magnitude compared with previous searches. The opportunity to make such a leap in sensitivity in tests of a global symmetry is rare and should not be missed.

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Note on strategy wording regarding fundamental physics at laboratories outside of CERN
The current strategy mentions the importance of national laboratories for smaller scale non-collider experiments. The European Spallation Source (ESS) is an international laboratory. It will have a fundamental physics program as this is part of its remit. A fundamental physics beamline is ranked as belonging to the highest priority for remaining beamlines to be allocated. The strategy wording should be changed to take this into account to avoid inadvertently putting users of the the ESS fundamental physics program at a disadvantage to users at comparable facilities when funding applications are made.

Scientific Context

Experiments at the LHC and beyond have so far confirmed the correctness of the non-neutrino sector of the Standard Model (SM). However, the well known problems of the SM remain and the paradigm of naturalness, the dominant motivation in the community for new physics at the TeV scale, is in tension with the data. Experimental physics thus finds itself at a critical juncture, unprecedented in 50 years. Moving to the next available energy frontier is no longer guaranteed to result in a new fundamental insight into nature. This situation has led to renewed emphasis on the importance of a broad complementary program of both high energy collider physics and smaller scale experiments at the intensity frontier, with the latter possessing a unique physics reach and ability to probe at mass scales substantially higher than at colliders. This document outlines one such experiment at the European Spallation Source (ESS), which searches for baryon number violation (BNV) [1]. The experiment would be carried out in two phases. HIBEAM (*High Intensity Baryon Extraction and Measurement)* is the first phase, comprising smaller-scale exploratory measurements and R&D for of the second stage, NNBAR at which the complete high-sensitivity program would be carried out. The experiment would make high sensitivity searches for BNV processes $n \rightarrow \bar{n}$ and $n \rightarrow n'$ (neutron to dark/sterile/mirror neutron)[2], corresponding to the selection rules in baryon number (B): $\Delta B = 2, 1$, respectively. The experiment would extend the $n \rightarrow \bar{n}$ sensitivity in oscillation probabilities by three orders of magnitude compared with previous searches and will search with cold neutrons for a new effect of $n \rightarrow n'$ transformation with a similar increase in sensitivity. The results can also be used to provide a sensitivity to matter stability of up to around 3×10^{35} years. The experiment addresses important open questions: baryogenesis[2,3,5], dark matter[6] as well as providing a probe for a new physics scale beyond that of colliders. This is a cross-disciplinary experiment with a clear particle physics goal, and is led by members of the collider community, but relying on expertise in nuclear physics, neutronics and magnetic shielding. The proposed work will also bring new methods and expertise used in high-energy physics to ESS and thus will cross-seminate the neutron technology development at ESS.

Baryon number violation

As a Sakharov condition, BNV is required to understand the matter-antimatter symmetry of the universe. Even within the SM baryon number is subject only to an approximate conservation law. At the perturbative level baryon number conservation arises due to the specific matter content in the SM, and corresponds to a so-called “accidental" symmetry, which may no longer hold when the SM is extended, in particular for unification theories. The SM itself in fact predicts BNV to occur via rare non-perturbative electroweak sphaleron processes (the quantum number ($B-L$) is respected by the SM and not B and L separately). Furthermore, precision tests of the Equivalence Principle offer no evidence for a long range force coupled to baryon number and thus a local gauge symmetry forbidding BNV. There is thus no reason to believe that B

[1] See [1] for the Expression of Interest for the experiment as originally proposed.
[2] See [2-4] for reviews on neutron-antineutron and neutron-sterile neutron searches.

is conserved and BNV can thus be expected to occur with very high confidence. Experiments must therefore take place which scan a range of selection rules and BNV-scales. A promising means of searching for BNV is via the observation of the $\Delta B \neq 0$ processes: neutron-antineutron ($\Delta B = 2$) and neutron-steriler neutron oscillations ($\Delta B = 1$). In these processes B is the only hitherto conserved quantity which is violated (in contrast with single nucleon decay searches which require simultaneous lepton number violation to balance angular momentum). A remarkable opportunity has emerged to pursue this at the ESS. The envisioned experiment's goal is to have at least a factor of 1000 greater sensitivity to the oscillation probabilities than previously obtained with free neutrons[4,7]. For neutron-antineutron oscillations, the last such experiment was performed in the early 1990s[7]. The critical technologies, advanced neutron optics and improved resolution trackers and calorimeters, already exist, and the ongoing work towards a technical proposal is focused on a cost-effective optimization of the experiment.

Neutron-antineutron oscillations

Neutron-antineutron oscillation features in a number of models of new physics. Examples include R-parity violating supersymmetry (RPV-SUSY)[8] and post-sphaleron baryogenesis[5]. Values of the BNV mass scale for observable oscillations beyond the current limits take place substantially exceed those attainable at colliders. Figure 1 demonstrates, in the framework of RPV-SUSY, the sensitivity of the NNBAR experiment to a new BNV-inducing mass scale. Other models that lead to an observable signature predict scales up to the grand unification scale at 10^{15} GeV[2,3].

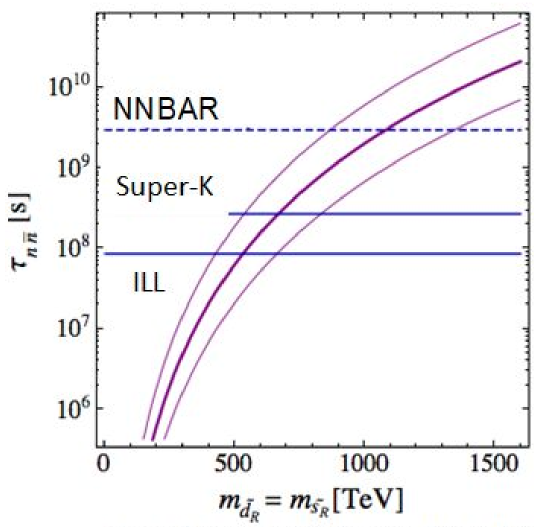

Figure 1: Sensitivity of the expected oscillation time sensitivty at NNBAR with mass scale for new physics. Limits from Super-Kamiokande and ILL are also shown.

Furthermore, there exists a symbiosis between neutron-antineutron oscillations and neutrino physics. A popular model explaining non-zero neutrino mass is the seesaw mechanism. In this approach neutrinos possess a Majorana component and L is violated by two units. Evidence for $\Delta L = 2$ processes are sought with, eg, neutrinoless double beta decay searches. Since Majorana neutrinos violate $(B-L)$ (the true anomaly-free SM symmetry) by two units it is natural to expect processes with $\Delta B = 2$. In addition to the complementarity with neutrino physics, this is predicted in extensions of the SM, such as lepton-quark unification models[2,3].

Setting aside the substantial theoretical motivation, a strictly experimental consideration of BNV hunting highlights the importance of neutron-antineutron oscillation searches. These searches are complementary to single nucleon decay searches (eg, $p \to \pi + e$), which require lepton number violation together with BNV, and therefore directly, but only, probe the Grand Unification scale, but are not relevant for baryogenesis since they conserve (B-L). Only searches for free neutron oscillation and anomalous nuclear decays, under the neutron oscillation or di-nucleon decay-hypothesis, offer high precision sensitivity to BNV-only processes. The most competitive limits for the free neutron oscillation time have hitherto been produced at Institut Laue Langevin (ILL) (0.86×10^8 s) [7] and Super-Kamiokande (2.7×10^8 s) [9]. The latter result used bound neutrons and a model-dependent correction for nuclear effects is needed to extract the free neutron oscillation bound. Of the class of experiments which search for BNV-only processes, free neutron oscillation searches possess both the cleanest experimental and theoretical environments in which to perform the search and quantify the results of the search. It is expected that the experiment, as in the previous instantiation, can be made background-free after data analysis selections.

Neutron-sterile neutron oscillations

The existence of a dark sector, interacting gravitationally, has long been postulated[10]. Portals to such a sector can occur via stable or meta-stable electrically neutral particles, which via an ultraweak mixing (new BSM mechanism), can convert into a dark partner particle. Photons may become “dark photons”. The neutron offers another possible portal, violating observable baryon number by one unit[4]. Demonstrating the existence of a dark sector via $n \to n'$ would have profound implications for understanding dark matter[6].

Objectives

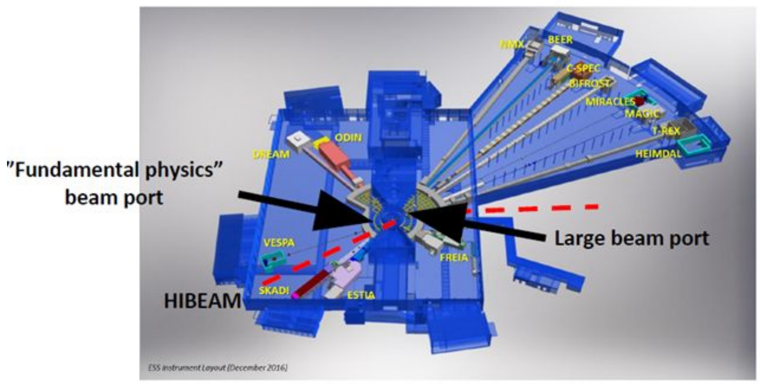

Figure 2: Outline of the beam ports of the ESS. The LBP (NNBAR, phase 2) and the beam port allocated for fundamental physics (HIBEAM, phase 1) are shown.

The fundamental objectives of the experiment are

- **Phase 1 (HIBEAM)** (i) Search for $n \to n'$ with a sensitivity in excess of that previously obtained in UCN experiment by new methods with cold neutrons at ESS. Using a reasonable 1m diameter detector and an operating power of only 1MW, limits from disappearance could be increased from ~20 s [4] to ~200 s with 1 month of measurement, while a regeneration search could achieve ~60 s after 1 month. Development of well characterized, high precision, large flux neutron counters will be an integral part of this research and design. (ii) Without exploiting any of time structure of the ESS pulsed beam, a search is possible for $n \to \overline{n}$ with a lower sensitivity to the oscillation probability than previously obtained at the ILL. Again using a reasonable 1m diameter detector and a 1MW operating power, this study could achieve ⅛ of previous ILL sensitivity per year and would be aimed at understanding the challenges (particularly the backgrounds) specific to this search at a pulsed source. The experiment would be used to optimise technology choices and background rejection methods in preparation for phase 2 (NNBAR). Both components of Phase 1 would offer an opportunity to understand the novel challenges of magnetic field uniformity, shielding, and control over long distances.

- **Phase 2 (NNBAR).** Search for $n \to \overline{n}$ with sensitivity to oscillation probabilities which are three orders of magnitude more sensitive than the previous searches with free neutrons. This experiment would run off the ESS Large Beam Port. A similar sensitivity increase is expected for $n \to n'$.

Methodology

The European Spallation Source

Currently under construction, the ESS is a multi-disciplinary research laboratory which will house the world’s most powerful neutron source. The ESS will produce a 2.86 ms long proton pulse with 2 GeV energy at a repetition rate of 14 Hz which impacts a rotating tungsten target. Spallation neutrons emerging from a system of moderators and reflectors are delivered to the beam ports and are then guided to the instruments. The various beam ports and instruments and experiments are shown in Figure 2.

The ESS is presently lacking a dedicated beamline for fundamental physics. However, as fundamental physics is an essential part of its goals, such a beamline is now ranked as belonging to the highest priority area for the next beamline call. A fundamental physics beam port has already been allocated, as shown in

Figure 2. A call for new beamline proposals is expected in 2019/2020 with a beamline becoming available in the mid 2020's.

The Large Beam Port, also shown in Figure 2, is a dedicated high flux beamline (2030-2033) which will become available after 2030. The construction of the LBP is now proceeding with an important investment by ESS with the assumption that NNBAR will find funding in the future. It is planned that the first stage, HIBEAM, would use the fundamental physics beamline (~2024-2028). The second stage of the experiment (NNBAR, ~2030-2034) would use the LBP. For convenience, the NNBAR stage is described first.

The NNBAR Experiment for neutron-antineutron oscillation

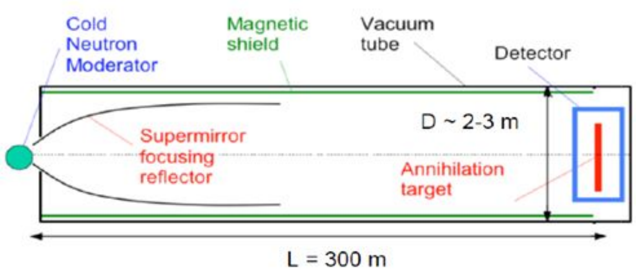

Figure 3: Schematic outline of experiment for neutron-antineutron oscillations at the NNBAR experiment.

Factor	Gain wrt ILL
Brightness	≥ 1
Moderator temperature	≥ 1
Target area	2
Angular acceptance/neutron transmission	40
Length	5
Run time	3
Total	≥ 1000

Table 1: Gain factors in $n \to \bar{n}$ oscillation probability for NNBAR compared with previous experiment at ILL.

The NNBAR experiment is schematically outlined in Figure 3. Neutrons are reflected by a "supermirror" focusing reflector into a magnetically shielded vacuum beam pipe over 300m to a target in which anti-neutrons would annihilate. Good focusing is critical as the neutron transit time or "clock" is reset via phase shifts occurring at a reflection on the guide wall. Development work is ongoing on metal-substrate-based supermirrors which have potential to further increase the experiments' sensitivity[12]. Magnetic shielding is necessary to suppress the energy split between neutron and antineutron states ($\Delta E = -2\mu \bullet B$) which would occur in a B-field due do the neutron's dipole moments $\pm\mu$, inhibiting the oscillation process[3]. A detector surrounding the detector target would record the final states emerging from an annihilation on carbon foil as well as monitoring background processes. The figure of merit for a neutron-antineutron search is $N_n t^2$ where N_n is the free neutron flux reaching the target and t is the average free flight time of the neutron. For a high sensitivity (high $N_n t^2$) search, the ESS satisfies the following key criteria

- A high intensity of cold neutrons from a bright source.
- A low source temperature (60K) providing larger neutron time of flight. The moderator will deliver a beam of slow, cold neutrons (energy < 5meV) at high intensity, maximising t and N_n , respectively. An overall lower neutron spectrum emission also increases the transport efficiency of the supermirror neutron reflector.
- The ESS Large Beam Port, corresponding to three standard beam ports, further increases the flux into the NNbar beamline, which, given the ESS site configuration, could extend up to 300m to maximize the neutron flight time. In addition, a running period of three ESS operating years is envisaged.

A number of factors drive the improvement in sensitivity of NNBAR compared to the last experiment at ILL. An important contribution to increased sensitivity is due to the use of a system of large elliptical focusing supermirror reflectors which direct off-axis neutrons to the detector with a single reflection. Furthermore, a

[3] A similar and massive degeneracy-breaking effect also arises due to the strong nuclear force for bound neutrons. This would suppress bound neutrons converting to anti-neutrons, ensuring matter stability.

larger detector with enhanced particle identification is possible, as is a longer running time. The gain with the ESS in comparison with the previous search at ILL is shown in Table 1. The overall gain is expected to exceed a factor 1000.

Neutronics

Advances in neutron supermirror technology over the past few decades help deliver the expected NNBAR sensitivity increase. A "butterfly" moderator design has been chosen which comprises cold regions of para-hydrogen and water at ambient temperature. It is important that the supermirror scatters neutrons from the cold regions associated with the moderators. In the current ESS plan, only an upper moderator will be installed for early running. A goal of the experiment is the installation in the lower slot of a second moderator, based on liquid deuterium, which will provide a stronger source of cold neutrons and thus increase further the sensitivity of NNBAR. The neutronics design will be adapted for this.

Magnetics The shielding concept comprises (i) an aluminum vacuum chamber; (ii) a two-layer passive magnetic shield made from magnetizable alloy with an approximate cylindrical cross section, mounted concentrically around the vacuum chamber with open ends; (iii) end sections made from a combination of passive and active components. To obtain a residual field of < 10 nT in the whole volume, the passive shield must be sufficiently strong to shield the quasi-static ambient magnetic field. A shield using two layers of 2 x 1 mm thick metal sheets with about 25 cm separation for an approximate diameter of 3.5 m with a transverse damping factor of 50-100 will be sufficient. The field inside the shield will be dominated by the magnetization of the inner shield layer, which can be removed by magnetic equilibration to the < 10 nT level.

The NNBAR Detector (2030-2034)

The detector needs to detect the presence of antineutrons in the beam with high efficiency while keeping the background level extremely low. The detection strategy is the same as used in the ILL experiment: antineutron annihilation in a target that is as transparent as possible to neutrons will lead to the production of three or more pions, with an average of five. The detector needs to reconstruct the pion momenta as accurately as possible, as the primary discriminating variables is the multi pion-system invariant mass after establishing the pions come from a common annihilation vertex. The major subsystems of the annihilation detector (radially in the outward direction - see Figure 4) are: (i) the annihilation target, (ii) the detector vacuum region inside the vacuum tube, (iii) the tracker, (iv) the time of flight system, (v) the calorimeter, (vi) the cosmic veto system and (vii) the trigger system. Requirements for these subsystems are formulated below. In general, the detector performance is well within current particle detector capabilities, but maximizing acceptance implies it will be large, and a careful cost versus performance optimization is being undertaken with with the aid of Monte Carlo detector simulations. (i) Annihilation Target. A good option is a uniform carbon disc with a thickness of ~ 100 μm and diameter ~ 2 m. It will be stretched on a low Z-material ring and installed in the center of the detector vacuum region. The material choice is driven by low capture cross section for thermal neutrons ~ 4 mb and high annihilation cross-section ~ 4 kb. Adding a few additional annihilation targets 10-20 cm downstream of

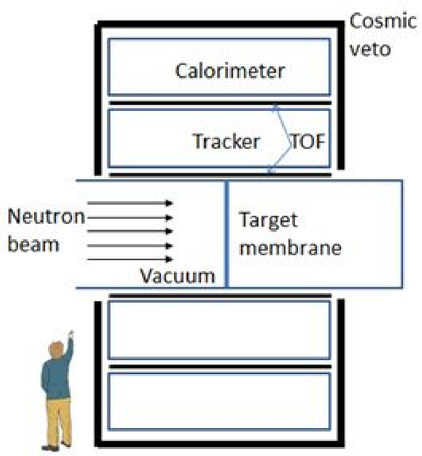

Figure 4: Schematic outline of the detector for neutron-antineutron oscillations at the NNBAR experiment.

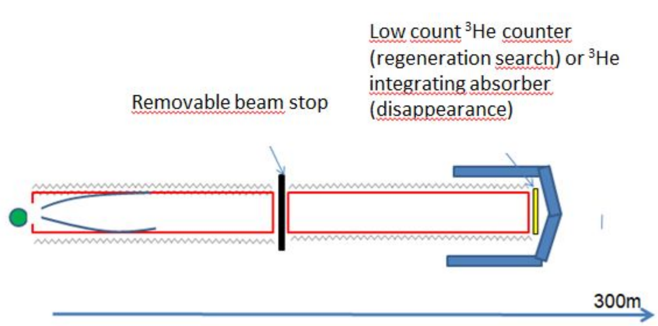

Figure 5: Schematic outline of NNBAR experiment for

the primary vertex could be valuable to measure backgrounds; this is under evaluation. (ii) Detector Vacuum Region. The detector vacuum region will be a tube with inner diameter ~ 2.5 m and wall thickness ~ 1.5 cm. The wall should be made of low Z material (e.g. Al) to reduce multiple scattering for tracking and provide a low (n,γ) cross section. Additional lining of the inner surface of the vacuum region with 6LiF pads will reduce the generation of γ's by captured neutrons. The detector vacuum region is expected to be the source of ~ 108 photons per second originating from neutron capture. Unlike in the neutron beam flight vacuum region, no magnetic shielding is required inside the detector vacuum region. The vacuum level should be 10^{-5} Pa via connection with the neutron beam vacuum region. (iii) Tracker. Accurate reconstruction of the annihilation vertex position is crucial in background rejection, as it affects the resolution on the invariant mass calculation and overall event momentum balance, and allows suppression of candidates resulting from single particles originating from nearby locations. The tracker is expected to extend radially from the outer surface of the detector vacuum tube by ~ 50 cm and have solid angle coverage of ~ 20°-160°. While the exact specifications will be refined using more detailed simulation, the rms accuracy on the annihilation vertex position (in the direction transverse to the beam) will probably be of order 1 cm, compared to 4 cm in ILL experiment. The candidate tracker technology is a time projection chamber. (iv) Time of Flight System. A time of flight system (TOF) will serve to suppress background induced by cosmic rays, as well as candidates resulting from single particles originating from nearby locations but slightly different times. The TOF will consist of two layers of fast detectors (e.g. plastic scintillation slabs or tiles) before and after the tracker with solid angle coverage of ~ 20°-160°. With appropriate segmentation, the TOF can provide directional information for all tracks found in the tracker. (v) Calorimeter. The calorimeter needs to accurately measure photon and pion energies to reconstruct each candidate annihilation event's invariant mass and momentum balance. It will provide trigger signals and energy measurements in the solid angle ~20°-160°. The average multiplicity of pions in annihilation at rest is five, so an average pion can be stopped in ~20 cm of dense material (like lead or iron). To contain low multiplicity (but small probability) annihilation modes, the amount of material needs to be slightly be larger. Calorimeter technology options include lead-scintillating fiber "spaghetti" or crystals. The detailed performance for the measurement of total energy of annihilation events and momentum balance in θ- and φ-projections will be determined from simulations and the technology choice will be made accordingly. (vi) Cosmic Veto System. The cosmic veto system will identify all cosmic ray background. It will likely be made of large plastic scintillator pads, and can possibly be recycled from existing experiments (Eg Double Chooz, Opera). Timing information can potentially be used to supplement the TOF. (vii) Trigger System. The ILL experiment already observed high single hit rates, so a somewhat more complex trigger system will be required. The advances in FPGA technology will make it possible to use all channels of all subdetectors in the trigger, and track and cluster reconstruction algorithms can be implemented. This will allow a highly selective trigger system to collect both signal and background control samples.

The NNBAR Experiment for neutron-sterile neutron oscillation The experiment can also be configured to search for $n \to n'$. This is a far simpler experimental set up, not requiring the sophisticated detector and magnetic field-free neutron transit though still requiring magnetic field control. A schematic diagram is given in Figure 5. The neutrons move through a region with fixed magnetic field. A beam stop absorbs neutrons. If $n \to n'$ has occurred then the sterile neutron can pass through the stop and regenerate into neutrons which can then be measured by a low count He-3 neutron detector at the end of the tube. An alternative operating mode is to remove the beam stop and use an integrating He-3 neutron detector to measure the flux at the end, inferring the existence of sterile neutrons by the disappearance of part of the flux.

HIBEAM The configuration of HIBEAM would be similar to that given for the full experiment albeit scaled down and without advanced neutronics. It would operate using the fundamental physics beamline allocated by the ESS which will give a transit length of 50m . This will still allow a competitive search for $n \to n'$. There will not give sufficient flux (or transit length) to match the ILL free $n \to \overline{n}$ limit. However, the fundamental aim is to determine source-specific backgrounds in-situ, validate prototype detector technologies and develop background rejection methods.

Readiness and Expected Challenges The NNBAR collaboration was formed in 2014, leading to an Expression of Interest in 2015[1], signed by around around 40 authors from 26 institutes at 8 countries. The experiment has subsequently developed into the two stage process described in this document which also includes sterile neutron searches. The co-spokespersons are Gustaaf Brooijmans (Columbia Uni.) and David Milstead (Stockholm Uni.); the lead scientist is Yuri Kamyshkov (Uni. of Tennessee). There is an interested and motivated community and preparatory work is ongoing on all aspects of the experiment. Although this is a multidisciplinary activity, it is led by particle physicists and has specific and important particle physics goals.

To move forward to the HIBEAM first phase, a fundamental physics beamline must be approved by the ESS. In the recent ESS "gap analysis" of missing beamlines, particle physics was given the highest priority for a future beam line. It is expected that such an approval will take place in 2020, with a usable beam line (for the less sophisticated neutron-sterile neutron search) in 2025-2026. The HIBEAM neutron-antineutron search and prototyping experiment would take place in 2026-2027. Discussions on fitting HIBEAM into the user program for a fundamental physics beamline have taken place since 2017. HIBEAM does not require beamtime for its program to the extent that it will inhibit other programs. HIBEAM is an inexpensive activity which can be achieved by a relatively modest investment from funding agencies (basic detector cost ~5 MEuros) with a small team (10-15 scientists and engineers).

The full experiment requires a collaboration of up to around one hundred scientists and engineers. The development of HIBEAM must therefore be accompanied by the growth of the collaboration. The presence of an approved and developing HIBEAM will be used to continue to attract collaborators. Engagement with national funding agencies is essential. As the NNBAR detector concept is finalised (~2028), memoranda of understanding and commitments are necessary. For both HIBEAM and NNBAR, approval from the ESS is of course necessary and appropriate steps must be taken to ensure integration of the experiments in the ESS program. NNBAR falls outside of the ESS instrument framework and special funding arrangements are needed.

Challenges to performing the experiment when full funding is secured are based on the need to design and construct the annihilation detector and the neutronics, including the development of appropriate metal-substrate-based supermirrors which have potential to further increase the sensitivity. Appropriate infrastructure changes must be made to ESS, such as shielding, to ensure that the LBP can be used without disturbing the other instruments. The primary data analysis challenge is the quantification of backgrounds at the spallation source and development of background rejection methods for a spallation source.

It may be possible to substantially reduce the size of the experiment or increase the sensitivity by a further order of magnitude by a judicious choice of materials for the long neutron transit guide such that neutrons can be reflected without the "neutron clock being reset" for the neutron-antineutron search[11]. A secondary program of very small scale scattering experiments with low energy antiprotons is needed to confirm the correctness and utility of this idea.

Timeline

A timeline is given below. Priority at the start of the program is given to the design and construction and exploitation of HIBEAM. However, R&D for the NNBAR phase will take place simultaneously with HIBEAM development and will be directly informed by the experiences of operating HIBEAM. Prior to the construction of HIBEAM and NNBAR, technical proposal (TP) and a technical design report (TDR) for each experiment will be produced. Not included in this timeline are milestones for ESS approval, which would be expected around the time of the TDRs . It should be noted that HIBEAM can be operated even with a fundamental physics beamline which is not fully furnished for the purposes of other particle physics experiments on that beamline.

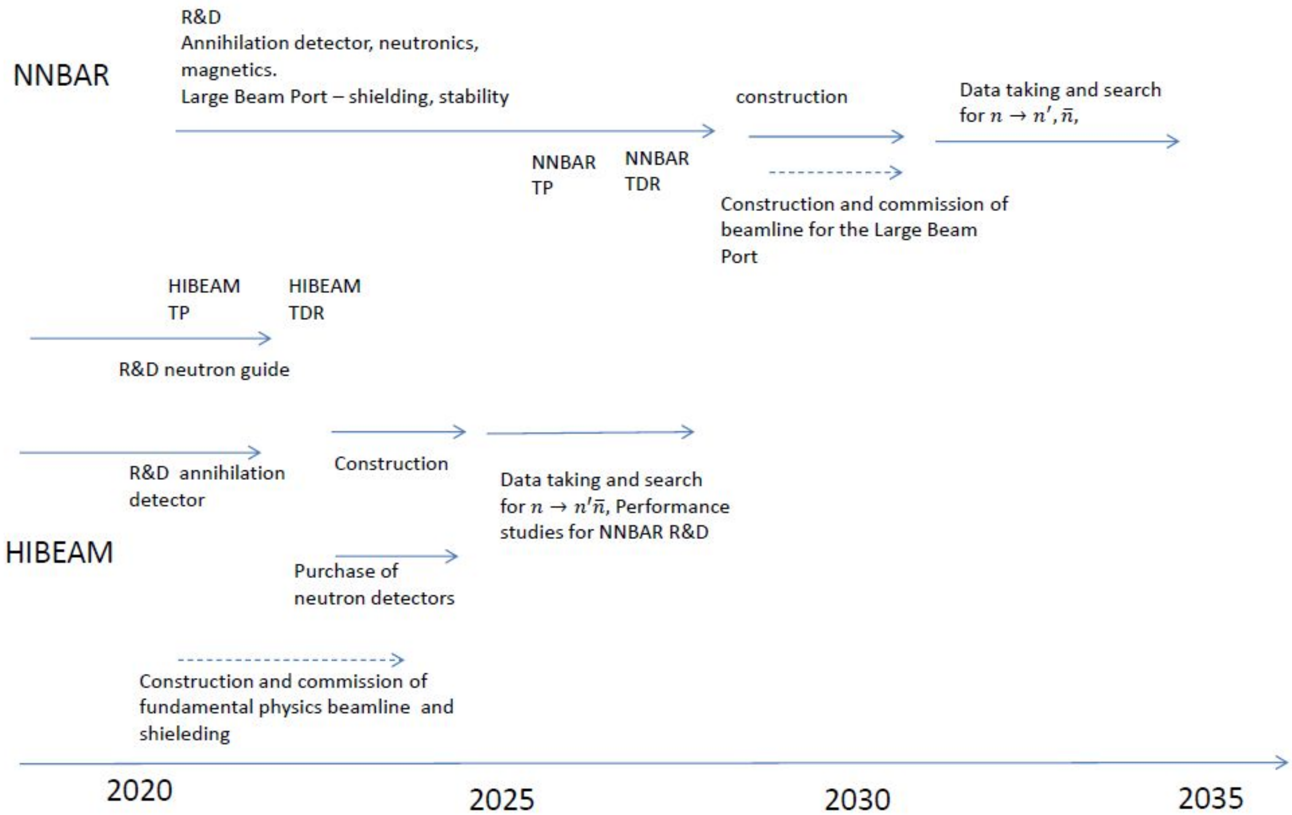

Figure 6: Timeline for development, construction and operation of HIBEAM and NNBAR.

Cost Estimate

An approximate detector cost breakdown is given in the table for HIBEAM. The costs are based on the simplest design with what is currently regarded as the minimum detector segmentation to achieve the physics goals.

Item	HIBEAM cost (kEuro)
R&D including component tests at external laboratories	500
Inner tracking chamber	500
Calorimeter	1500
Scintillators	200
Magnetic shielding and field control	1500
Neutron counters and integrators	500

Total ~5 MEuros

Table 2: Approximate cost estimate for construction of HIBEAM. Infrastructure costs for the beamline are not included.

The total component costs is around 5MEuros. In addition, it is estimated that at least 2.5 FTE's per year for a five year period are required. Costs associated with the furnishing of the beamline and neutron shielding and associated operating costs would be expected to be covered by the ESS in its beamline development.

A complete costing for the second stage NNBAR experiment is yet to be made. However, a number of remarks can be made. The magnetic shielding cost would be expected to scale with length, approaching thus 9

MEuros. It is possible that much of the prototype detector can be reused. However, given that the first stage is a prototype experiment it is conceivable that a new technology choice may be employed rendering detector cost estimates at this stage unreliable. The first stage does not use advanced neutronics whereas it is anticipated that a high grade neutron supermirror system will be deployed for the NNBAR phase of the experiment. As the quality and design of the supermirrors is still being developed, a cost estimate is unreliable. However, it will likely be of the order of several MEuro. Furthermore, whilst the first stage takes advantage of a fundamental physics beamline funded and commissioned as part of the ESS' regular suite of instruments, the NNBAR stage sits outside of this framework. Therefore it is expected that costs will have to be met concerning neutron and radiation shielding given that an entirely new beam port, the Large Beam Port which is equivalent to three standard-sized ports, will be used. The shielding may also impact on the performance of the other ports and such effects must be studied and, if necessary, mitigated.

Interested Community

The community is diverse and multidisciplinary, encompassing physicists from large collider experiments to low energy nuclear experiments together with scientists specialising in neutronics and magnetics. European, US and Asian communities are represented. A list of interested scientists who believe the project should be considered in the long term planning for particle physics is listed below.

Joshua Barrow (University of Tennessee, USA), David Baxter (Indiana University, USA), Zurab Berezhiani (Univ. L'Aquila and LNGS/INFN, Italy), Torsten Bringmann (Oslo University, Norway), Gustaaf Brooijmans (Columbia University, USA) , Leah Broussard (Oak Ridge National Laboratory, USA), Lorenzo Calibbi (Beijing, Inst. Theor. Phys., China), Gabriele Ferretti (Chalmers University of Technology, Sweden), Peter Fierlinger (Technical University of Munich, Germany), Alexey Fomin (PNPI, Russia), Bogdan Fornal (Henryk Niewodniczański Institute of Nuclear Physics, Polish Academy of Sciences, Poland),Matt Frost (Oak Ridge National Laboratory,, USA), Alfredo Galindo-Uribarri (Oak Ridge National Laboratory, USA), Peter Geltenbort (Institut Laue Langevin, France), Timothy Greenshaw (University of Liverpool, United Kingdom), Elena Golubeva (INR, Moscow), Lawrence Heilbronn (University of Tennessee, USA), Leif Jönsson (Lund University, Sweden), Tord Johansson (Uppsala University, Sweden), Yuri Kamyshkov (University of Tennessee, USA),Mishima Kenji (KEK, Japan), Masaaki Kitaguchi, (Nagoya University , Japan), Esben Klinkby (Technical University of Denmark, Denmark), Adam Kozela (Henryk Niewodniczański Institute of Nuclear Physics, Polish Academy of Sciences, Poland), Mats Lindroos (European Spallation Source, Sweden), Chen-Yu Liu (Indiana University, USA), Bastian Märkish (Technical University of Munich, Germany), Bernhard Meirose (Lund University, Sweden), David Milstead (Stockholm University, Sweden), Rabindra Mohapatra (University of Maryland, USA), Valery Nesvizhevsky (Institut Laue-Langevin, France), Anders Oskarsson (Lund University, Sweden), Krzysztof Pysz (Henryk Niewodniczański Institute of Nuclear Physics, Polish Academy of Sciences, Poland), Jean-Marc Richard (Institut de Physique Nucléaire, and University of Lyon, France), Alexander Saunders (Los Alamos National Laboratory, USA),Hirohiko M. Shimizu (Nagoya University, Japan), Anatoly Serebrov (PNPI, Russia), David Silvermyr (Lund University, Sweden), Samuel Silverstein (Stockholm University, Sweden), William Mike Snow (Indiana University, USA) , Anca Tureanu (University of Helsinki, Finland), Shaun Vavra (University of Tennessee, USA), Richard Wigmans (Texas Tech Uni, USA), Yutaka Yamagata, (RIKEN, Japan), Albert Young (North Carolina State University, USA).

Conclusions

The construction of the ESS, coupled with progress which has taken place in neutronics and detector technology, make it possible to search for baryon number violation via $n \rightarrow \overline{n}$ oscillations, with a sensitivity three orders of magnitude beyond the current limit. Similar improvements are expected for $n \rightarrow n'$ searches. Opportunities to make improvements of this magnitude in the testing of a conservation law are rare and should be pursued.

References

[1] Expression of Interest for a new search for neutron-antineutron oscillations at the ESS, G. Brooijmans *et al.*, https://www.nevis.columbia.edu/~gusbroo/nnbar/papers/nnbar_ESS_EoI_Apr15.pdf

[2] Neutron-Antineutron Oscillations: Theoretical Status and Experimental Prospects
D.G. Phillips *et al.*, Phys.Rept. 612 (2016) 1-45

[3] Neutron-Anti-Neutron Oscillation: Theory and Phenomenology
R.N. Mohapatra, J.Phys. G36 (2009) 104006

[4] New experimental limits on neutron - mirror neutron oscillations in the presence of mirror magnetic field Z. Berezhian *et al.*, Eur.Phys.J. C78 (2018) no.9, 717
[5] Post-Sphaleron Baryogenesis and an Upper Limit on the Neutron-Antineutron Oscillation Time
K.S. Babu, P.S. Bhupal Dev, Elaine C.F.S, R.N. Mohapatra, Phys.Rev. D87 (2013) no.11, 115019
[6] Constraints on Mirror Models of Dark Matter from Observable Neutron-Mirror Neutron Oscillation
R. N. Mohapatra and Shmuel Nussinov, Phys.Lett. B776 (2018) 22-25
[7] M. Baldo-Ceolin et al., Z. Phys. C 63 (1994) 409.
[8] Baryon number violation in supersymmetry: n-nbar oscillations as a probe beyond the LHC,
L. Calibbi *et a*l., JHEP 1605 (2016) 144, Erratum: JHEP 1710 (2017) 195 ;
Baryon number violation in supersymmetry: Neutron-antineutron oscillations as a probe beyond the LHC L. Calibbi *et al.*, PoS LHCP2016 (2016) 152
[9] K. Abe et al. [Super-Kamiokande Collaboration], Phys. Rev. D 91 (2015) 072006
[10] Working Group Report: New Light Weakly Coupled Particles
Rouven Essig (YITP, Stony Brook) et al., arXiv:1311.0029 [hep-ph]
[10] Takuya Hosobata, Norifumi L. Yamada, Masahiro Hino, Yutaka Yamagata, Toshihide Kawai, Hisao Yoshinaga, Koichiro Hori, Masahiro Takeda, Shin Takeda, and Shin-ya Morita Development of precision elliptic neutron-focusing supermirror, Optics Express, vol.25,(17), pp20012-20024, (2017)
[11] A new operating mode in experiments searching for free neutron-antineutron oscillations based on coherent neutron and antineutron mirror reflections
V.V. Nesvizhevsky *et al.*, Published in EPJ Web Conf. 191 (2018) 01005