The HIBEAM/NNBAR program



D. Milstead Stockholm University

- Why look for neutron oscillations ?
- How to look for neutron oscillations
- Nnbar and HIBEAM at the ESS

Baryon and lepton number violation

- *BN,LN* "accidental" SM symmetries at perturbative level
 - *BNV*, *LNV* in SM non-perturbatively (eg sphalerons)
 - *B*-*L* is conserved, not *B*, *L* separately.
- *BNV* needed for baryogenesis (Sakharov condition)
- *BNV,LNV* generic features of SM extensions (eg SUSY)
- Need to explore the possible selection rules:

$$\Delta B \neq 0, \Delta L = 0, \Delta [B - L] \neq 0$$

$$\Delta B = 0, \Delta L \neq 0, \Delta [B - L] \neq 0$$

$$\Delta L \neq 0, \Delta B \neq 0, \Delta [B - L] = 0$$

••••

BNV,LNV selection rules



$n \rightarrow \overline{n}$: SM and beyond

Symbiosis in the SM

• Proton decay, neutrinoless double beta decay, and $n \rightarrow \overline{n}$

• Electroweak sphaleron process: QQQQQQ QQQL LL~ $(p \rightarrow e + \pi) \times (n \rightarrow \overline{n}) \times (v \rightarrow \overline{v})$ EFT: dimension 9 operator



Probe PeV scale





How to look for $n \rightarrow \bar{n}$: mixing formalism



$$\begin{split} &i\hbar \frac{\partial}{\partial t} \binom{n}{\bar{n}} = \binom{E_n \quad \delta m}{\delta m \quad E_{\bar{n}}} \binom{n}{\bar{n}} \\ &\delta m = \langle \bar{n} | H_{eff} | n \rangle < 10^{-29} \text{ MeV} = n\bar{n} \text{ mixing physics} \\ &P_{n \to \bar{n}} = \left(\frac{\delta m}{\Delta E}\right)^2 \sin^2(\Delta E \times t) \quad ; \Delta E = E_n - E_{\bar{n}} \end{split}$$

Free neutron oscillation: Quasi-free limit : $\Delta Et \sim 1 \Rightarrow P \sim (\delta m \times t)^2$ Slow neutrons, propagating over a long distance $\tau_{n \to \bar{n}} > 0.86 \times 10^8$ s (ILL)

Bound neutron oscillation: Suppression: $\left(\frac{\delta m}{\Delta E}\right)^2 < 10^{-60}$ Best current limits (SuperKamiokande) $\Rightarrow \tau_{free} > 4.7 \times 10^8$ s Model-dependent (nuclear interactions).

The European Spallation Source

High intensity spallation neutron source

Multidisplinary research centre with 17 European nations participating.

Lund, Sweden. Under ci.

2 GeV protons (3ms long pulse, 14 Hz) hit rotating tungsten target.

Cold neutrons after interaction with moderators.





Beamlines and program





R&D

Annihilation detector prototype Conceptual design reports for HIBEAM/NNBAR TDRs and small scale experiment at ESS test beamline

HIBEAM High precision induced: $n \rightarrow n', n \rightarrow \overline{n}$ (x10 improvement) First search for free $n \rightarrow \overline{n}$ at a spallation source

Eg at upgraded test beamline

NNBAR High sensitivity free $n \rightarrow \overline{n}$ (x1000 improvement) At the Large Beam Port

The NNBAR Experiment



Multi-disciplinary environment needed.

Geant-4 detector simulation



A Computing and Detector Simulation Framework for the HIBEAM/NNBAR Experimental Program at the ESS

Ioshua Barrow^{10,11}, Gustaaf Brooijmans², José Ignacio Marquez Damian³, Douglas DiJulio³, Katherine Dunne⁴, Elena Golubeva⁵, Yuri Kamyshkov¹, Thomas Kittelmann³, Esben Klinkby⁸, Zsófi Kókai³, Jan Makkinje², Bernhard Meirose^{4,6,*}, David Milstead⁴, André Nepomuceno⁷, Anders Oskarsson⁶, Kemal Ramic³, Nicola Rizzi⁸, Valentina Santoro³, Samuel Silversein⁴, Alan Takibayev³, Richard Wagner⁹, Sze-Chun Yiu⁴, Luca Zanini³, and

EPJ Web of Conferences 251, 02062 (2021) CHEP 2021



Status of the Design of an Annihilation Detector to Observe Neutron-Antineutron Conversions at the European Spallation Source

Sze-Chun Yiu ^{1,4}⁽⁶⁾, Bernhard Meirose ^{1,2,4}⁽⁶⁾, Joshua Barrow ^{1,4}⁽⁶⁾, Christian Bohm ¹, Gustaaf Brooijmans ⁸, Katherine Dunne ¹⁽⁶⁾, Elena S. Golubeva ⁸, David Milstead ¹, André Nepomuceno ¹⁽⁶⁾, Anders Oskarsson ², Valentina Saturo ^{2,4}⁽⁶⁾ and Samuel Silverstein ¹⁽⁶⁾

Symmetry 14 (2022) 1, 76

Backgrounds

- Cosmic rays (neutral and charged dominant at ILL)
- Thermal neutrons, beta-delayed neutrons
- Low energy photons from the activation of the target + beamline.
 - Low energy (1 MeV) but 10^{10} photons/s are expected
 - Pile-up
- Spallation bg -high energy, can be removed with timing
- Nuclear fragments





Capability of the experiment

Gain in $P_{n\bar{n}} \sim 10^3$ compared with ILL.



Increase in sensitivity for $P_{n\bar{n}} \sim 10^3$ compared to previous experiment (ILL) Stability of matter (τ_{life}) sensitivity $\sim 10^{35}$ yrs Discovery or new stringent limit on models of new physics and stability of matter.

HIBEAM

Search for sterile neutron oscillations at HIBEAM



Getting to HIBEAM

• VR RFI

- ESS, LU, CTU, UU, SU
- Detector prototype development and testing
 - Time Projection Chamber
 - Hybrid Scintillator Lead Glass Calorimeter
 - Integrated DAQ design
- Annihilation detector design simulations
- Neutron detector choice
- Beamline design







McStas Simulations Cold Neutrons propagated from the butterfly moderator

HIBEAM/NNBAR

New high-sensitivity searches for neutrons converting into antineutrons and/or sterile neutrons at the European Spallation Source

- Developed from an Expression of Interest for a $n \rightarrow \bar{n}$ at the ESS (2015). Signatories from 26 institutes , 8 countries.
- Developed into multi-stage HIBEAM/NNBAR
 - Major effort SV,FR,DK,DE,US
 - Co-spokespersons G. Brooijmans (Columbia), D. Milstead (Stockholm)
 - Lead scientist (Y. Kamyshkov, Tennessee)
 - Technical Coordinator (V. Santoro, ESS)
- HIBEAM is supported by the Swedish Research Council (1.4MEuro) from the Swedish Research Council
- NNBAR is supported as part of a 3MEuro H2020 for an upgraded ESS with a new lower moderator

CDRs for NNBAR (2023) and HIBEAM (2024) in preparation

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- Pre-CDR white paper: *J. Phys.G* 48 (2021) 7, 070501 See also:
- JINST 17 (2022) 10, P10046 (Arxiv: 2209.09011, [physics.ins-det))
- Proc AccApp 21 (arXiv: 2204.04051 [physics.ins-det))
- Symmetry 14 (2022) 1,76
- Proc vCHEP2021, EPJ Web Conf. 251 (2021) 02062, Arxiv: 2106.15898 [physics.ins-det])

Summary

- Neutron oscillations are a key but rarely explored portal for new physics
 - B, B-L violation, baryogenesis, BSM physics, dark matter
- The ESS is opening a new discovery window
- HIBEAM/NNBAR is a multidisciplinary program to increase sensitivity by ~1000
- Such a leap in sensitivity in tests of a global symmetry is rare !

A. The quest for dark matter and the exploration of flavour and undamental symmetries are crucial components of the search for new physics. This search can be done in many ways, for example through precision measurements of flavour physics and electric or magnetic dipole moments, and searches for axions dark sector candidates and feebly interacting particles. There are many options to address such physics topics including energy-ironiter colliders, accelerator and non-accelerator experiments. A diverse programme that is complementary to the energy frontier is an essential part of the European particle physics Strategy. Experiments in such diverse areas that offer potential high-impact particle physics programmes at laboratories in Europe should be supported, as well as participation in such experiments in other regions of the world. an particle physics

The 2020 Update to the European Particle Physics Strategy ("Essential activities")

- Prototype work ongoing
- CDRs for NNBAR (2023) and HIBEAM (2024) in preparation

NNBAR – the Large Beam Port



Photograph of the frame of the Large Beam Port being installed in the ESS monolith. A superimposed CAD drawing is showing the field of view of the LBP. The upper moderator, the inner shielding to avoid a direct view of the target, and the space below the target where the high-intensity moderator will be placed, can be clearly seen.

The need for magnetic shielding





Degeneracy of *n*, \bar{n} broken in B–field due to dipole interactions: $\Delta E = 2\vec{\mu} \cdot \vec{B}$

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Flight time \leq 1s
For quasi-free condition \Delta E \times t \ll 1
\Rightarrow B \leq 10nT and vacuum \leq 10^{-5} Pa.
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Outer and inner octagon-shaped passive shield of 1-2 mm thick sheets of mumetal.



Fitting into the European landscape



Plug the "observable gap" for B,L tests

+ sensitivity to many theories of physics beyond the SM (eg hidden sector (dark matter), SUSY, unification models, neutrino mass models etc.)

The 2020 Update to the European Particle Physics Strategy (Essential activities)

A. The quest for dark matter and the exploration of flavour and fundamental symmetries are crucial components of the search for new physics. This search can be done in many ways, for example through precision measurements of flavour physics and electric or magnetic dipole moments, and searches for axions dark sector candidates and feebly interacting particles. There are many options to address such physics topics including energy-frontier colliders, accelerator and non-accelerator experiments. A diverse programme that is complementary to the energy frontier is an essential part of the European particle physics Strategy. Experiments in such diverse areas that offer potential high-impact particle physics programmes at laboratories in Europe should be supported, as well as participation in such experiments in other regions of the world.