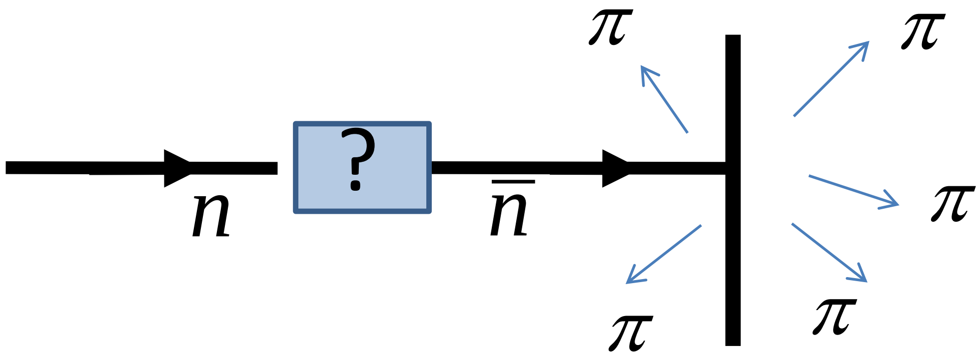
The HIBEAM/NNBAR experiment to look for induced conversions of neutrons to sterile neutrons and antineutrons



D. Milstead

Stockholm University

- Why look for neutron oscillations ?
- HIBEAM/NNBAR at the ESS

Baryon and lepton number violation

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

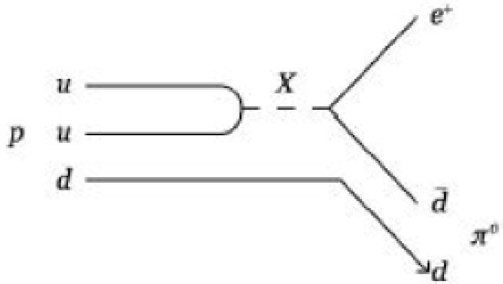
$$\Delta B \neq 0\ ,\ \Delta L = 0,\ \Delta\left[B - L\right] \neq 0$$

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

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

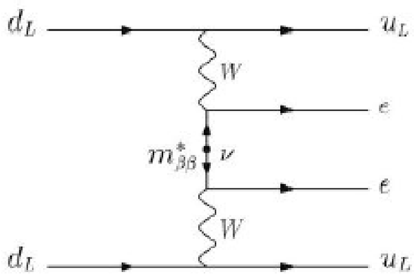
.....

Complementary BNV, LNV observables



$p \to e^{+} + \pi^{0}$

$\Delta B \neq 0, \Delta L \neq 0$

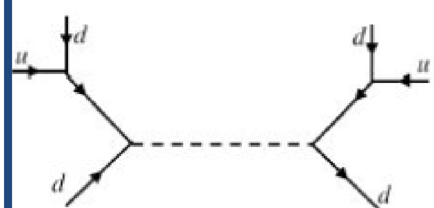


$0\nu 2\beta$

$\Delta B = 0, \Delta L \neq 0$

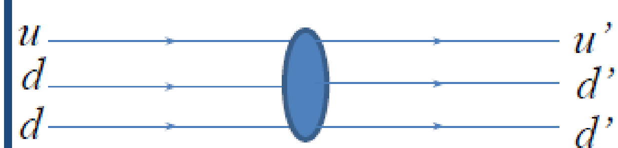
Symbiosis

Neutron oscillation



$n \to \bar{n}$

$\Delta B = 2, \Delta L = 0$

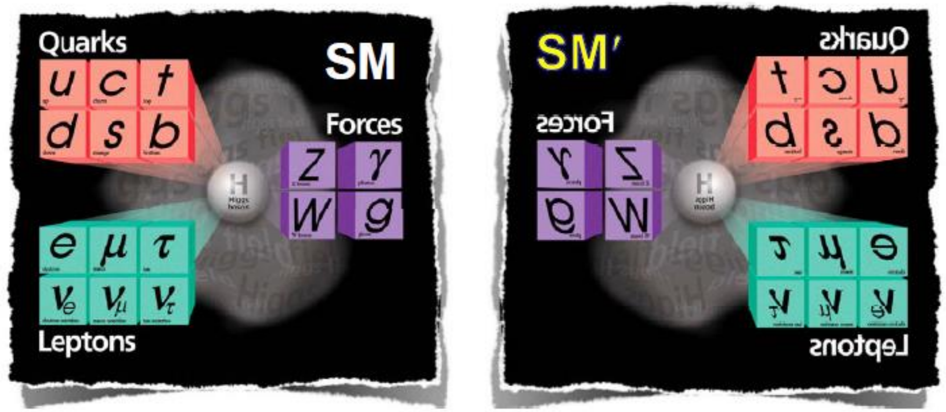


$n \to n'$ (mirror)

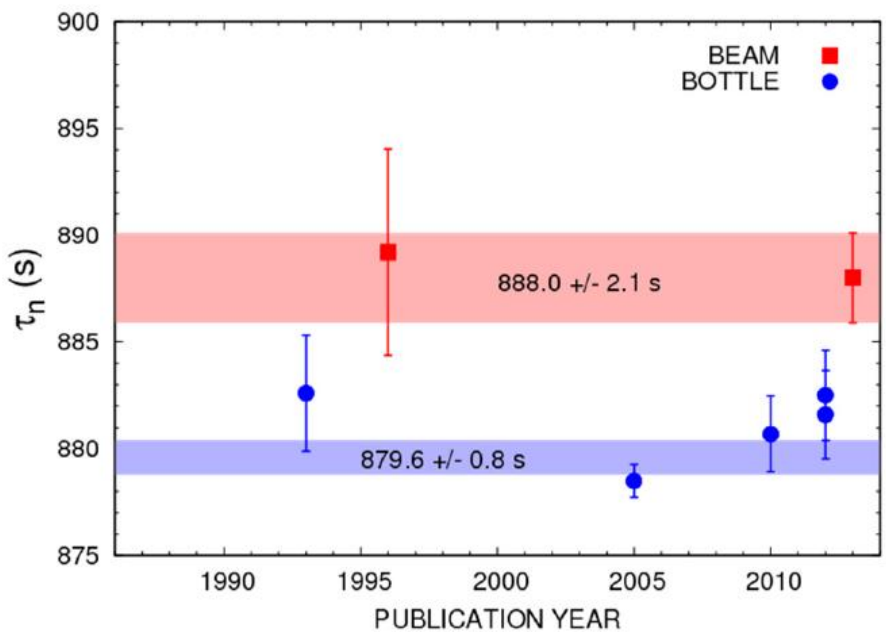
$\Delta B = 1, \Delta L = 0$

Sterile neutrons

Eg “Hidden/mirror” sector.
Generic search for dark/sterile sector via neutrons :
copiously produced and quasi-stable electrically neutral particles



Can explain 5σ neutron lifetime discrepancy seen in bottle and beam experiments.



Neutron-antineutron oscillations

- R-parity violating supersymmetry, minimal flavour violation SUSY
- Unification models: $M \sim 10^{15}$ GeV
- Left-right symmetric models ($n\bar{n}$ and $0\nu 2\beta$)
- Extra dimensions models
- Post-sphaleron baryogenesis
- etc, etc: [arXiv:1410.1100]

High precision $n \to \bar{n}$ search

$\Rightarrow$ Scan over wide range of phase space for generic BNV

+

$\Rightarrow$ model constaints.

Neutron mixing

$$\hat{\mathscr{H}} = \begin{pmatrix} E_n & \varepsilon_{n\bar{n}} \\ \varepsilon_{n\bar{n}} & E_{\bar{n}}, \end{pmatrix}.$$

Free $n \to \bar{n}$

$$P_{n\bar{n}}(t) = \varepsilon_{n\bar{n}}^2 t^2 = \frac{t^2}{\tau_{n\bar{n}}^2} = \left(\frac{t}{0.1\ \mathrm{s}}\right)^2 \left(\frac{10^8\ \mathrm{s}}{\tau_{n\bar{n}}}\right)^2 \times 10^{-18};$$

$$\hat{\mathscr{H}} = \begin{pmatrix} m_n + \vec{\mu}_n \vec{B} & \varepsilon_{n\bar{n}} & \alpha_{nn'} & \alpha_{n\bar{n}'} \\ \varepsilon_{n\bar{n}} & m_n - \vec{\mu}_n \vec{B} & \alpha_{n\bar{n}'} & \alpha_{nn'} \\ \alpha_{nn'} & \alpha_{n\bar{n}'} & m_{n'} + \vec{\mu}_{n'} \vec{B}' & \varepsilon_{n\bar{n}} \\ \alpha_{n\bar{n}'} & \alpha_{nn'} & \varepsilon_{n\bar{n}} & m_{n'} - \vec{\mu}_{n'} \vec{B}' \end{pmatrix}$$

Induced with B-field:
$n \to \bar{n}$, $n \to n'$

$$P_{n\bar{n}}(t) = \frac{1}{4}\alpha_{n\bar{n}'}^2 \alpha_{n\bar{n}'}^2 t^4 \sin^2\beta = \frac{\sin^2\beta}{4}\left(\frac{t}{0.1\ \mathrm{s}}\right)^4 \left(\frac{10^2\ \mathrm{s}^2}{\tau_{nn'}\tau_{n\bar{n}'}}\right)^2 \times 10^{-8}$$

The European Spallation Source

High intensity spallation neutron source

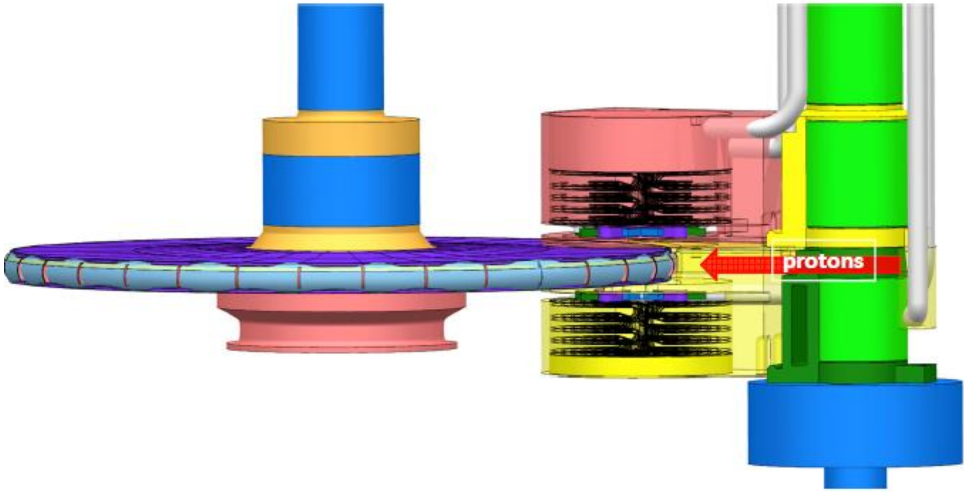
Multidisplinary research centre with 17 European nations participating.

Lund, Sweden.
Start operations in 2027/2028.

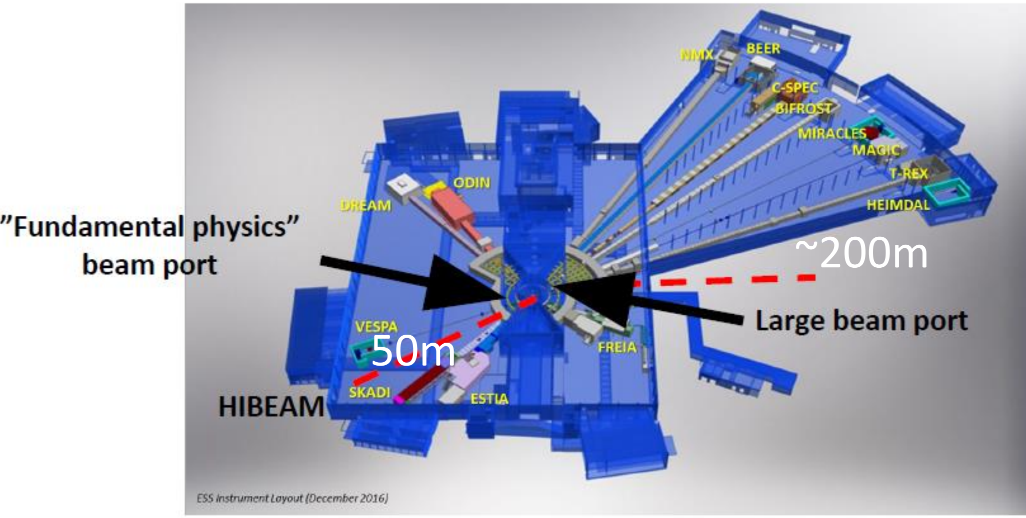
2 GeV protons (3ms long pulse, 14 Hz) hit rotating tungsten target.

Cold neutrons after interaction with moderators.

ess
EUROPEAN
SPALLATION
SOURCE



Beamlines and program



R&D
Annihilation detector prototype
Conceptual design reports for HIBEAM/NNBAR

TDR
Small scale experiments at ESS test beamline

2024

2028

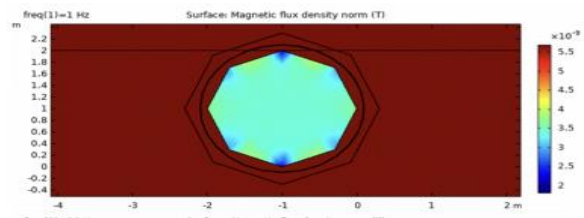
HIBEAM
High precision induced:
$n \rightarrow n'$, $n \rightarrow \bar{n}$ (x10 improvement)
Low sensitivity free $n \rightarrow \bar{n}$

NNBAR
High sensitivity free $n \rightarrow \bar{n}$ (x1000 improvement)

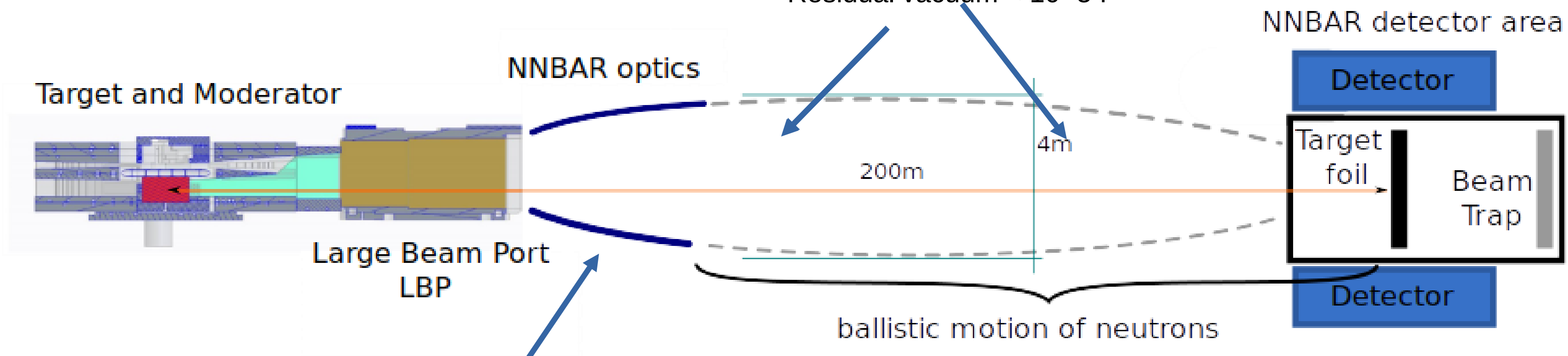
>2028

>2030

NNBAR Experiment

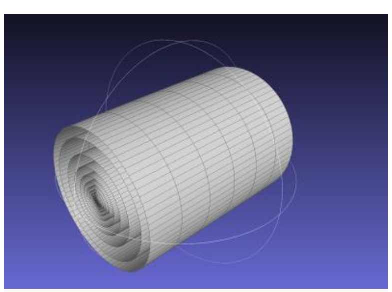


Residual B field <10 nT
Residual vacuum < 10 -5 P



free from perturbing
magnetic stray fields, interaction with walls
and ambient gas particles

Reflector Optics
collect large solid angle of emitted neutrons and re-focus to detector area

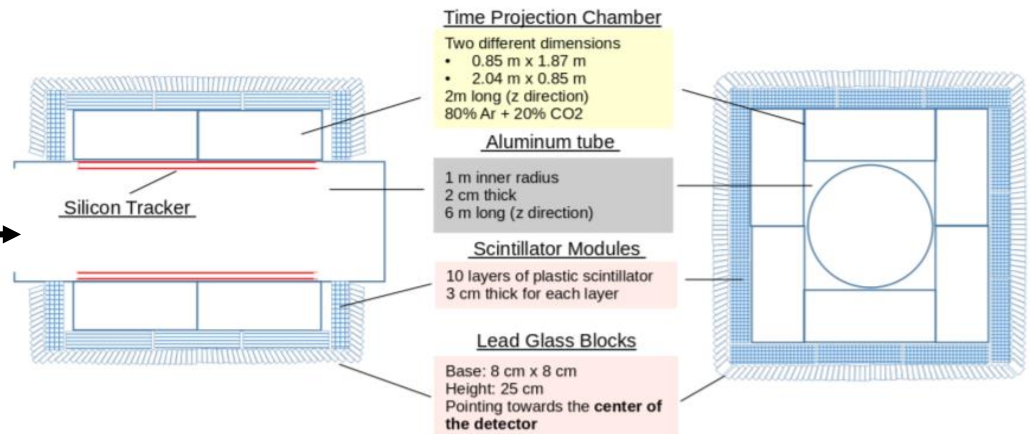


Annihilation detector

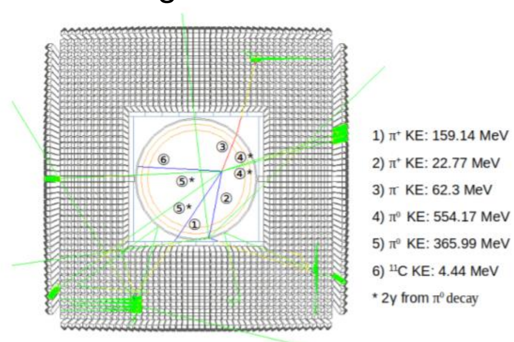
Signal: 1-2 GeV c.o.m. energy , 4-7 pions

- Baseline detector
  - Silicon tracker
  - TPC
  - Scintillator range detector
  - Lead-glass calorimeter

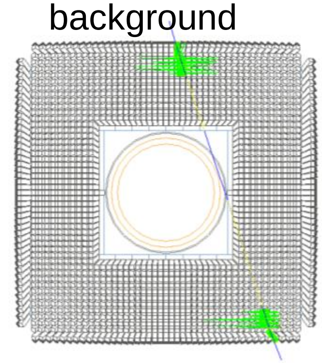
$\bar{n}$



Signal



Cosmic muon background



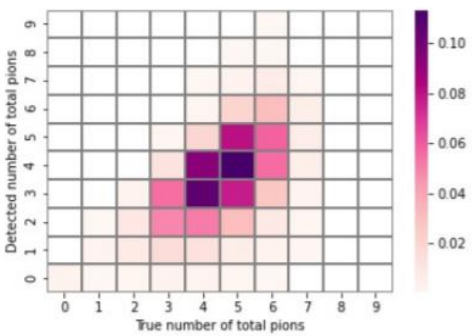
- Requirements
  - Reconstruction of multi-pion final state
  - Invariant mass reconstruction
  - Particle identification
  - Timing sensitivity to reject cosmics and other out-of-time backgrounds

Prototype under construction: arXiv:2107.02147 [physics.ins-det].

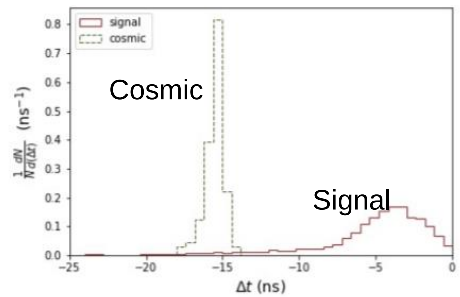
For HIBEAM stage can also borrow existing detector, eg WASA detector

Geant-4 detector simulation

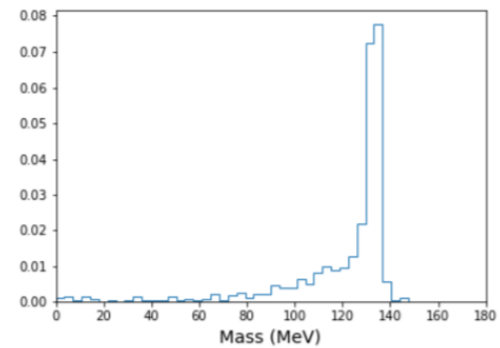
Pion multiplicity

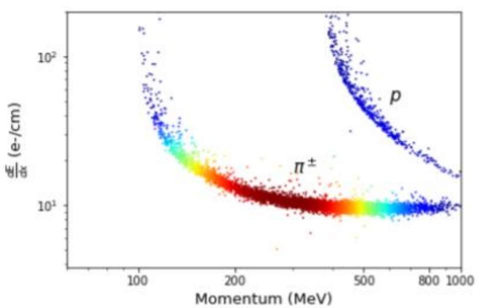


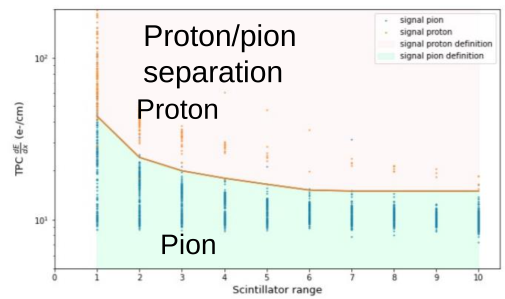
Event timing

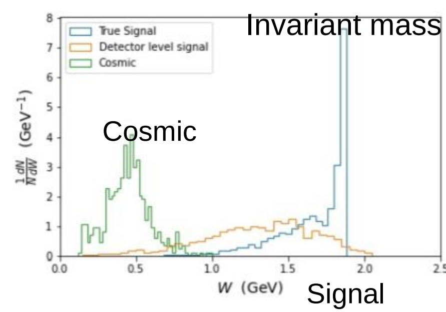


π^0 mass reconstruction









Geant 4 model designed and reproducing well expected distributions

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

Joshua Barrow[10,11], *Gustaaf* Brooijmans[2], *José Ignacio Marquez* Damian[3], *Douglas* DiJulio[3], *Katherine* Dunne[4], *Elena* Golubeva[5], *Yuri* Kamyshkov[1], *Thomas* Kittelmann[3], *Esben* Klinkby[8], *Zsófi* Kókai[3], *Jan* Makkinje[2], *Bernhard* Meirose[4,6,*], *David* Milstead[4], *André* Nepomuceno[7], *Anders* Oskarsson[6], *Kemal* Ramic[3], *Nicola* Rizzi[8], *Valentina* Santoro[3], *Samuel* Silverstein[4], *Alan* Takibayev[3], *Richard* Wagner[9], *Sze-Chun* Yiu[4], *Luca* Zanini[3], and

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

symmetry

Article

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

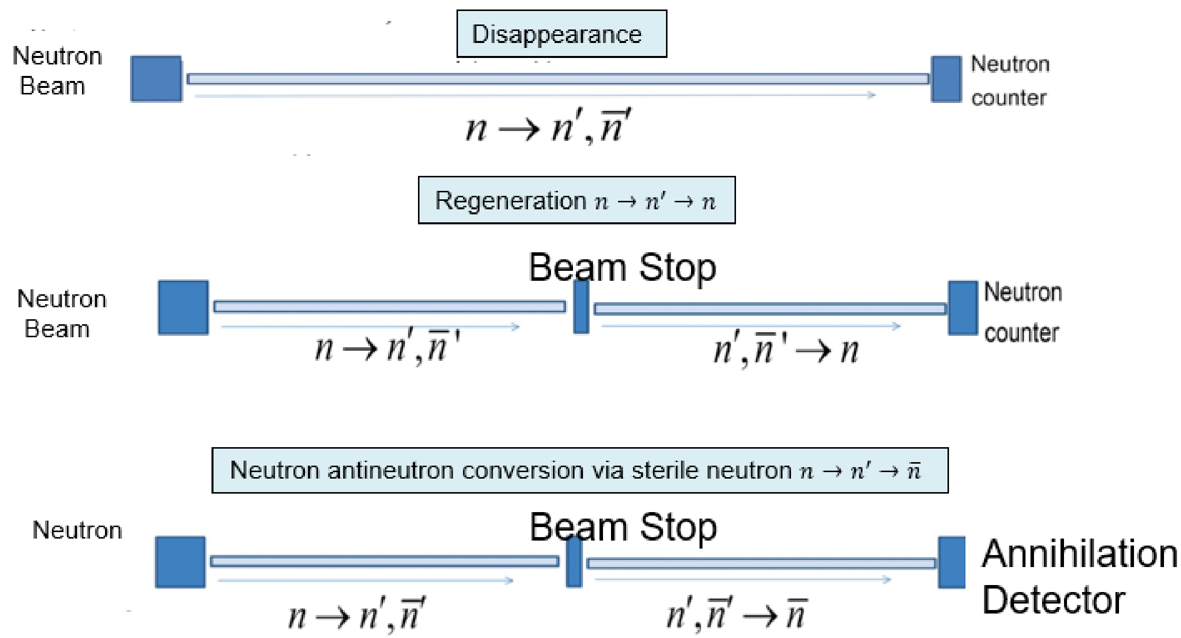
Sze-Chun Yiu [1,*], Bernhard Meirose [1,2,*], Joshua Barrow [3,4], Christian Bohm [1], Gustaaf Brooijmans [5], Katherine Dunne [1], Elena S. Golubeva [6], David Milstead [1], André Nepomuceno [7], Anders Oskarsson [2], Valentina Santoro [2,8] and Samuel Silverstein [1]

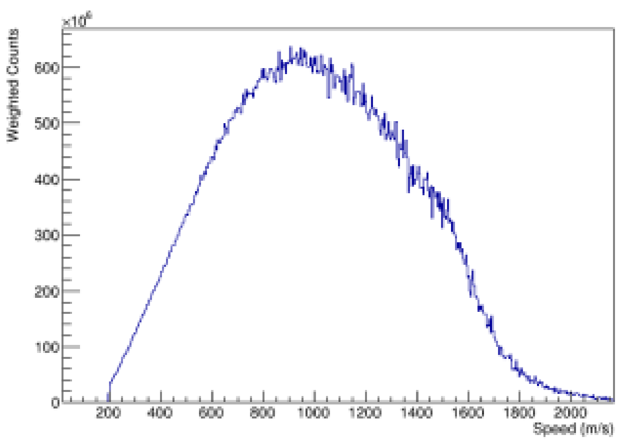
Symmetry 14 (2022) 1, 76

Search for sterile neutron oscillations at HIBEAM

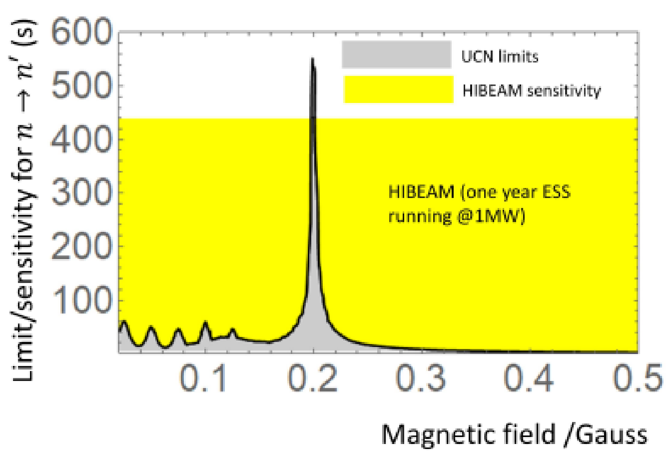
Complementary suite of searches to constrain mixing Hamiltonian

$$\hat{\mathscr{H}} = \begin{pmatrix} m_n + \vec{\mu}_n \vec{B} & \varepsilon_{n\bar{n}} & \alpha_{nn'} & \alpha_{n\bar{n}'} \\ \varepsilon_{n\bar{n}} & m_n - \vec{\mu}_n \vec{B} & \alpha_{n\bar{n}'} & \alpha_{nn'} \\ \alpha_{nn'} & \alpha_{n\bar{n}'} & m_{n'} + \vec{\mu}_{n'} \vec{B}' & \varepsilon_{n\bar{n}} \\ \alpha_{n\bar{n}'} & \alpha_{nn'} & \varepsilon_{n\bar{n}} & m_{n'} - \vec{\mu}_{n'} \vec{B}' \end{pmatrix}$$





Neutron speed



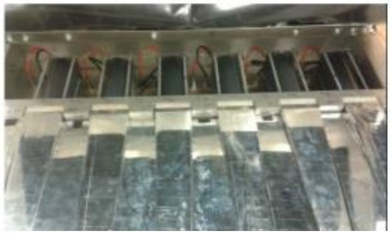
Sensitivity

Beamline of ANNI design

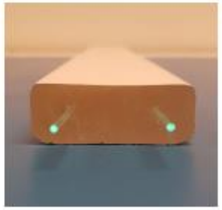
Investigations of different designs ongoing

Prototype and testing

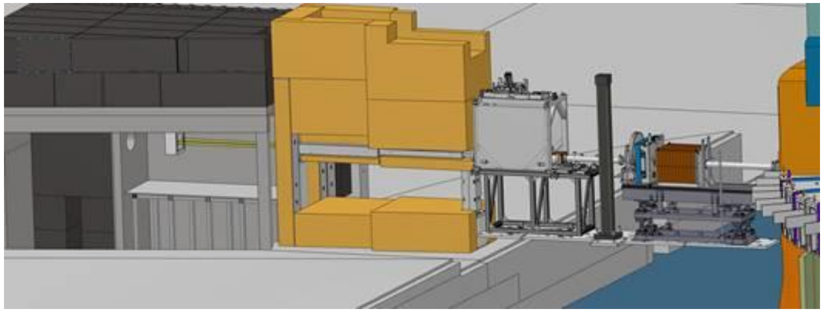
- Time Projection Chamber (LU)
  - Prototype TPC at Lund read out with GEMs
  - Studies on response to thermal/fast neutrons
  - GEM pad shapes using cosmics



- ASA Scintillating EM Calorimeter (UU)
  - 24 CsI WASA Experiment crystals being recommissioned for studies of Detector Option 3



- Hybrid Scintillator - Lead Glass Calorimeter (SU)
  - Hadronic Range Detector scintillator staves readout with WLS + SiPMs
  - Lead glass EM calorimeter
    - Lead glass blocks read out with SiPM arrays
- Integrated DAQ design
- Testing for cosmics and sources



- Future tests at ESS test beam line

HIBEAM/NNBAR

- 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

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

A. Addazi[h,at], K. Anderson[aq], S. Ansell[bm], K. S. Babu[az], J. Barrow[w], D. V. Baxter[d,e,f], P. M. Bentley[ac], Z. Berezhiani[b,l], R. Bevilacqua[ac], R. Biondi[b], C. Bohm[ba], G. Brooijmans[an], L. J. Broussard[aq], B. Dev[ay], C. Crawford[z], A. D. Dolgov[ai,ao], K. Dunne[ba], P Fierlinger[o], M. R. Fitzsimmons[w], A. Fomin[n], M. Frost[aq], S. Gardiner[c], S. Gardner[z], A. Galindo-Uribarri[aq], P. Geltenbort[p], S. Girmohanta[bb], E. Golubeva[ah], G. L. Greene[w], T. Greenshaw[aa], V. Gudkov[k], R. Hall-Wilton[ac], L. Heilbronn[x], J. Herrero-Garcia[be], G. Ichikawa[bf], T. M. Ito[ab], E. Iverson[aq], T. Johansson[bg], L. Jönsson[ad], Y-J. Jwa[an], Y. Kamyshkov[w], K. Kanaki[ac], E. Kearns[g], B. Kerbikov[al,aj,ak], M. Kitaguchi[ap], T. Kittelmann[ac], E. Klinkby[ae], A. Kobakhidze[bl], L. W. Koerner[s], B. Kopeliovich[bi], A. Kozela[y], V. Kudryavtsev[ax], A. Kupsc[bg], Y. Lee[ac], M. Lindroos[ac], J. Makkinje[an], J. I. Marquez[ac], B. Meirose[ba,ad], T. M. Miller[ac], D. Milstead[ba,*], R. N. Mohapatra[j], T. Morishima[ap], G. Muhrer[ac], H. P. Mumm[m], K. Nagamoto[ap], F. Nesti[l], V. V. Nesvizhevsky[p], T. Nilsson[r], A. Oskarsson[ad], E. Paryev[ah], R. W. Pattie, Jr.[t], S. Penttilä[aq], Y. N. Pokotilovski[am], I. Potashnikova[bi], C. Redding[x], J-M. Richard[bj], D. Ries[af], E. Rinaldi[au,bc], N. Rossi[b], A. Ruggles[x], B. Rybolt[u], V. Santoro[ac], U. Sarkar[v], A. Saunders[ab], G. Senjanovic[bd,bn], A. P. Serebrov[n], H. M. Shimizu[ap], R. Shrock[bb], S. Silverstein[ba], D. Silvermyr[ad], W. M. Snow[d,e,f], A. Takibayev[ac], I. Tkachev[ah], L. Townsend[x], A. Tureanu[q], L. Varriano[i], A. Vainshtein[ag,av], J. de Vries[a,bh], R. Woracek[ac], Y. Yamagata[bk], A. R. Young[as], L. Zanini[ac], Z. Zhang[ar], O. Zimmer[p]

[a]*Amherst Center for Fundamental Interactions, Department of Physics, University of Massachusetts, Amherst, MA, USA*
[b]*INFN, Laboratori Nazionali del Gran Sasso, 67010 Assergi AQ, Italy*
[c]*Fermi National Accelerator Laboratory, Batavia, IL 60510-5011, USA*
[d]*Department of Physics, Indiana University, 727 E. Third St., Bloomington, IN, USA, 47405*
[e]*Indiana University Center for Exploration of Energy & Matter, Bloomington, IN 47408, USA*
[f]*Indiana University Quantum Science and Engineering Center, Bloomington, IN 47408, USA*
[g]*Department of Physics, Boston University, Boston, MA 02215, USA*
[h]*Center for Theoretical Physics, College of Physics Science and Technology, Sichuan University, 610065 Chengdu, China*

- Pre-CDR white paper:*J.Phys.G* 48 (2021) 7, 070501

See also:

- 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

- HIBEAM/NNBAR
  - Two stage experiment
  - Rare opportunities to improve sensitivity by three orders of magnitude on a global symmetry.
  - Funded development under way for CDR
  - Collaborators welcome !!
  - Fits well in the overall strategy for particle physics

Update to the Strategy for European Particle Physics

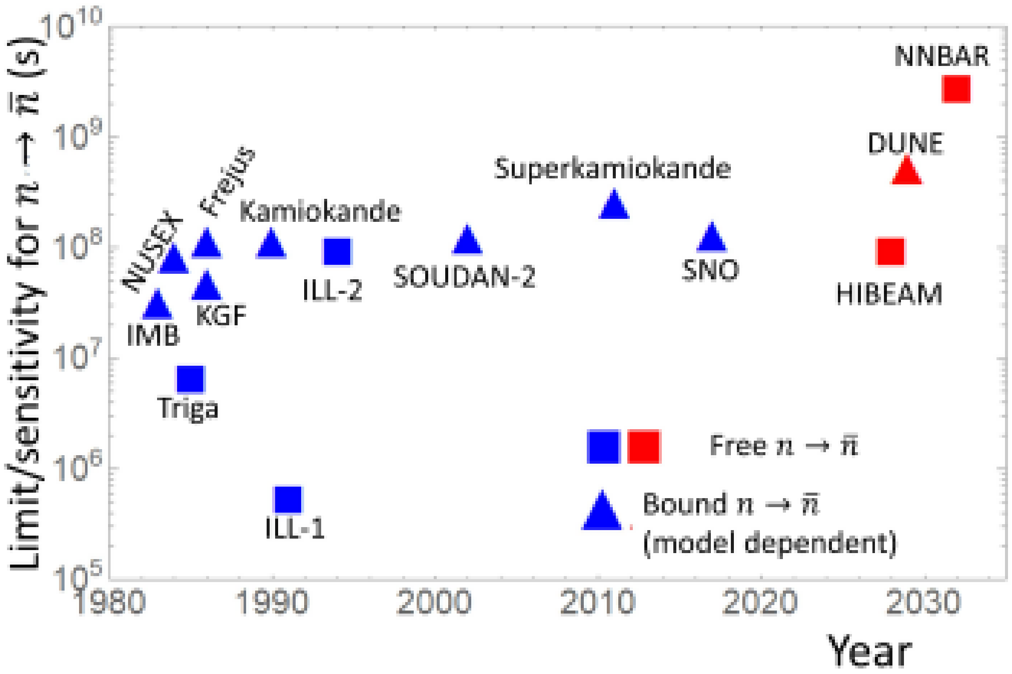
“Essential activities”

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.***

Bonus slides

Ongoing and planned activities

- Annihilation detector prototypes
- Further developments of optics, magnetics, and moderator designs
- Background campaign
  - Shielding designs using Comblayer
  - High energy spallation backgrounds, Cosmics, Gamma bg from activation, delayed beta decays, skyshine ….
  - Zero bg experiment at the ILL (1990’s)
  - Aim to reproduce this.



An experimentalist's view

Hypothesis: baryon number is weakly violated. How do we look for it ?

Need processes in which only BNV takes place.

Single nucleon decay searches, eg, $p \to \pi^0 + e^+$?

$\Rightarrow$ $|\Delta B| = 1$, $|\Delta L| = 1$!

Decays without leptons, eg, $p \to \pi + \pi,$ impossible due to angular momentum conservation.

$|\Delta B| \neq 0$, $\Delta L = 0$ observables restricted by Nature.

$n \to \bar{n}, n'$ and dinucleon decay searches sensitive to BNV-only.

Free $n \to \bar{n}, n'$ searches $\Rightarrow$ cleanest experimental and theoretical approach.