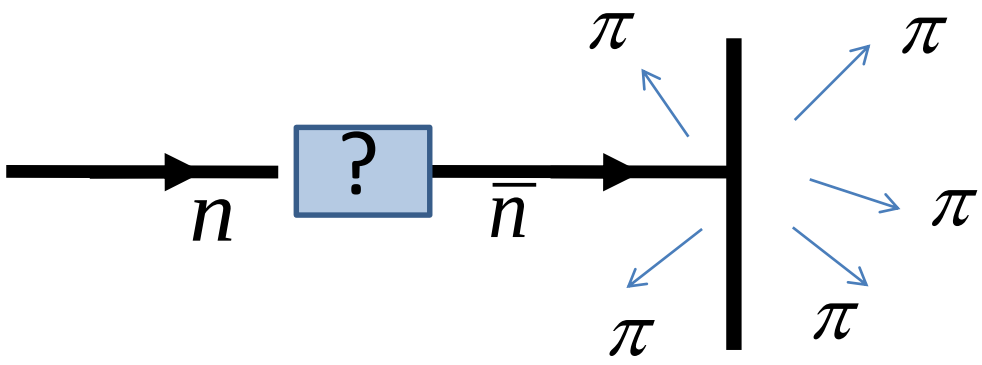
Searching for neutrons conversions and baryon number violation at the ESS with the HIBEAM/NNBAR experiment



D. Milstead
Stockholm University

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

Neutron conversions and baryon number violation

- Baryon number ”accidental” symmetry in the Standard Model
- Baryon number violation
  - BNV generic features of SM extensions
  - Sakharov condition for baryogenesis
- Neutron conversions
  - “Pure” BNV $(\Delta B \neq 0\,, \Delta L = 0)$
  - Free $n \to \bar{n}\ \ (\Delta B = 2)$
    - Post-sphaleron baryogenesis
    - SUSY, extra dimensions
    - LR unification models
    - Symbiosis with $0\nu2\beta$ decay $(\Delta L = 2)$
  - $n \to n'\ (\Delta B = 1), n \to n' \to \bar{n}\ \ (\Delta B = 2)$
    - quasi-stable uncharged particle can mix with a dark sector
    - cogenesis scenarios
    - mirror matter

Ingredients for searches for neutron conversions

- A copious source of neutrons
- Control of fields in which the neutrons propagate
- Long beamlines to give the neutrons time to convert

A copious source of neutrons: the European Spallation Source

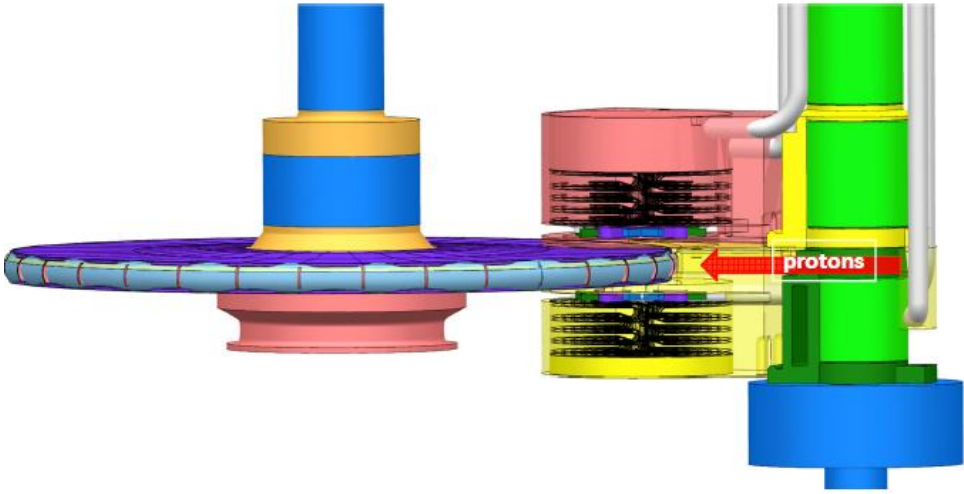
High intensity spallation neutron source

Multidisplinary research centre with 17 European nations participating.

Lund, Sweden.
Start operations in 2026/2027.

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

Cold neutrons after interaction with moderators.
~$10^{12\text{-}13}$ n/s .



Control of fields in which the neutrons propagate

Eg Free $n \longrightarrow \bar{n}$ state

$$\Psi = \begin{pmatrix} n \\ \bar{n} \end{pmatrix} \qquad H = \begin{pmatrix} E_n & \varepsilon \\ \varepsilon & E_{\bar{n}} \end{pmatrix}$$

ε =mixing mass term

Probability to find an antineutron at time t is given by

$$P_{n\bar{n}}(t) = \frac{\varepsilon_{n\bar{n}}^2}{(\Delta E/2)^2 + \varepsilon_{n\bar{n}}^2} \sin^2\left[t\sqrt{(\Delta E/2)^2 + \varepsilon_{n\bar{n}}^2}\right] e^{-t/\tau_n},$$

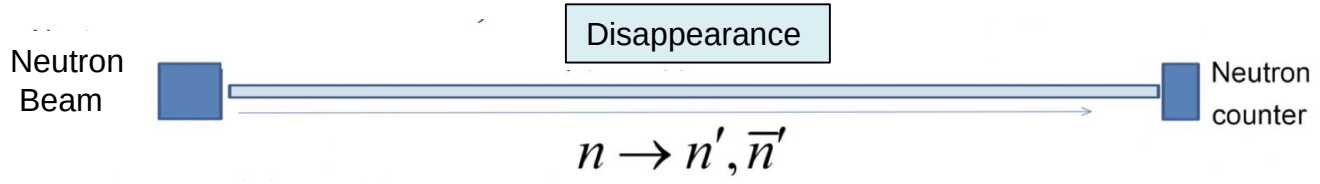
$\Delta E = E_n - E_{\bar{n}}$ Require degeneracy between n, $\bar{n}$

⇒ Zero magnetic field (<10^{-5} G)

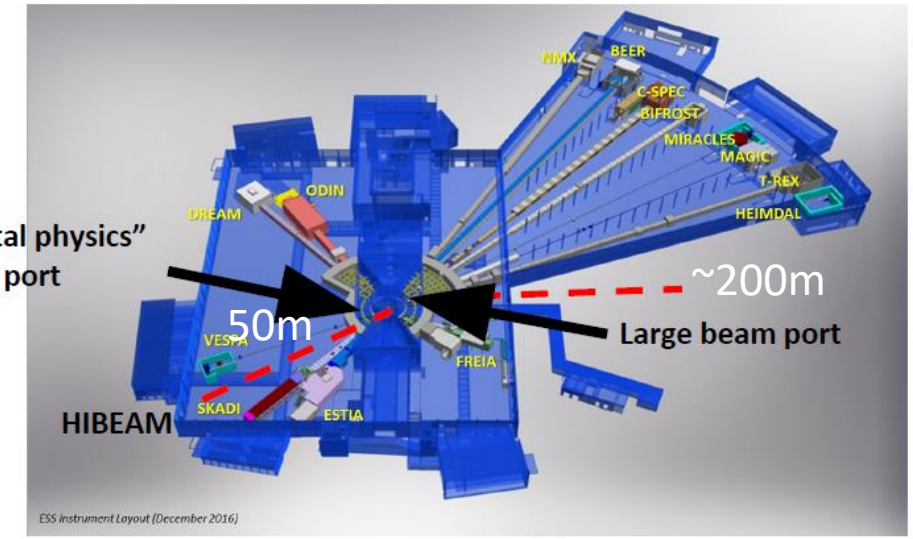
Similarly for $n \longrightarrow n'$

Magnetic field in dark sector

⇒ Scan for -1G <B<+1G in ~mG steps



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 $n \rightarrow n'$(x10 improvement)
Low sensitivity free $n \rightarrow \bar{n}$

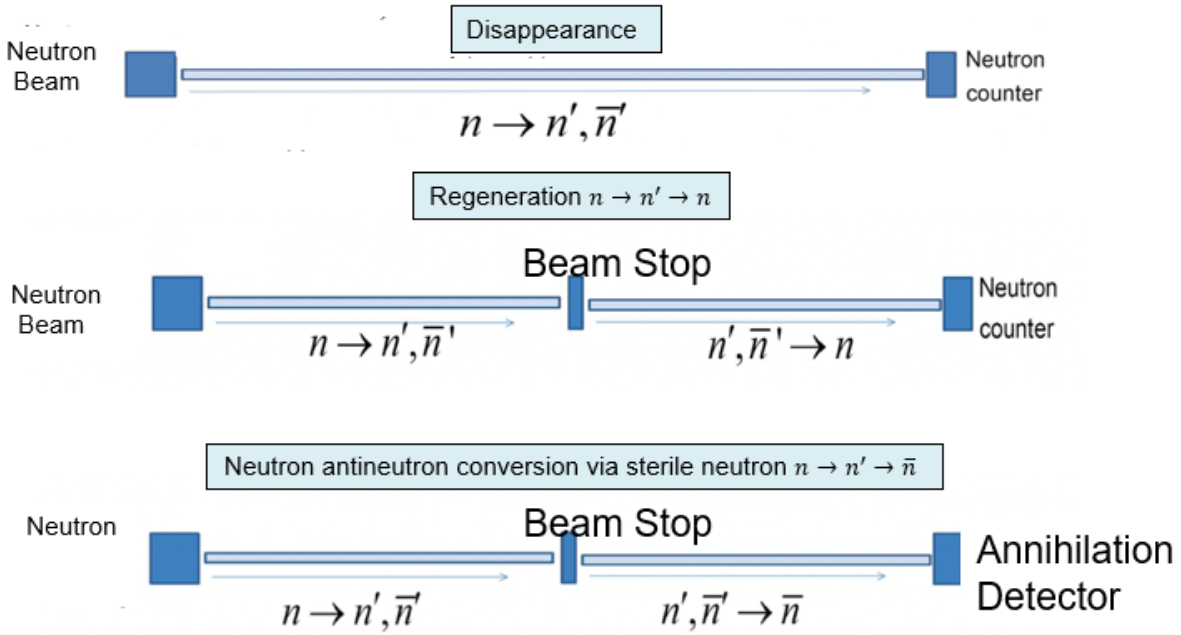
NNBAR
High sensitivity free $n \rightarrow \bar{n}$ (x1000 improvement)

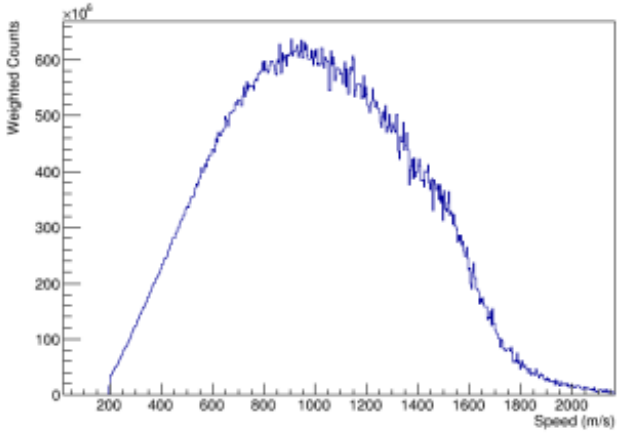
>2028 >2030

Search for sterile neutron oscillations at HIBEAM

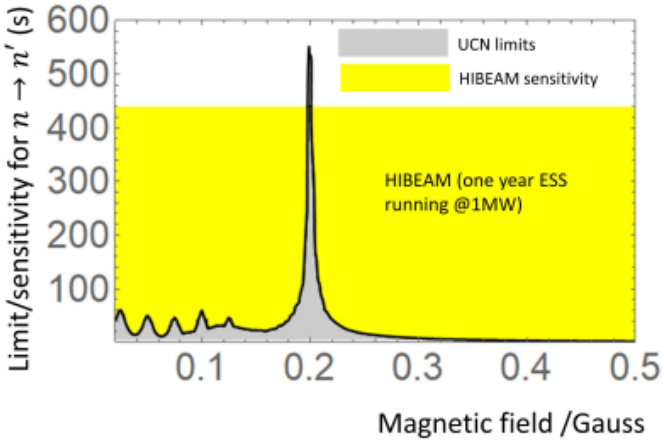
Complementary suite of searches to constrain mixing Hamiltonian

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





Neutron speed



Sensitivity

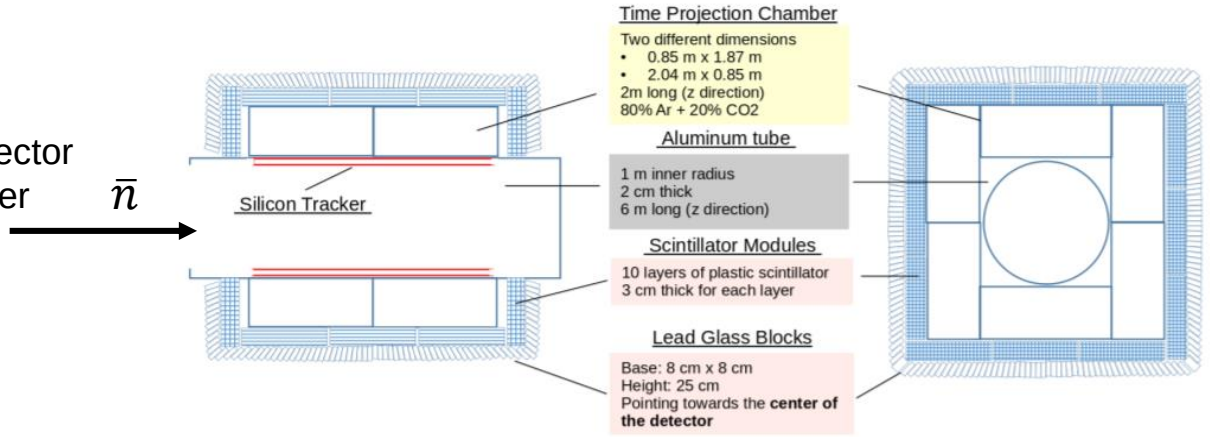
Beamline of ANNI design
Investigations of different designs ongoing

Annihilation detector

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

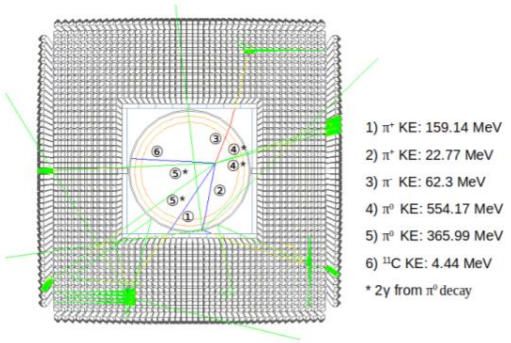
- Baseline detector
  - Silicon tracker
  - TPC
  - Scintillator range detector
  - Lead-glass calorimeter

$\bar{n}$

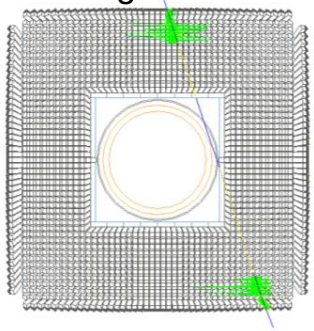


- Requirements
  - Reconstruction of multi-pion final state
  - Invariant mass reconstruction
  - Particle identification
  - Timing sensitivity to reject cosmics and other out-of-time backgrounds

Signal



Cosmic muon background

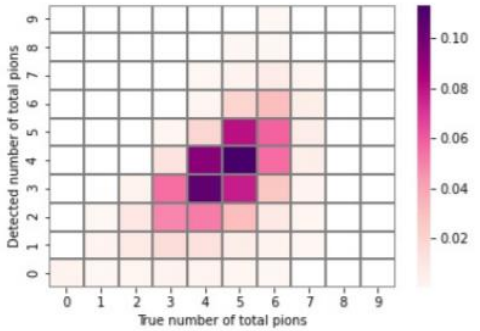


Prototype under construction: arXiv:2107.02147 [physics.ins-det].

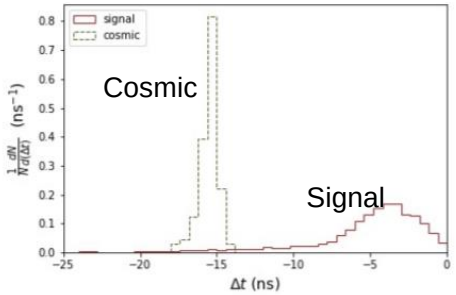
For HIBEAM stage can also borrow existing detector, eg WASA detector

Geant-4 detector simulation

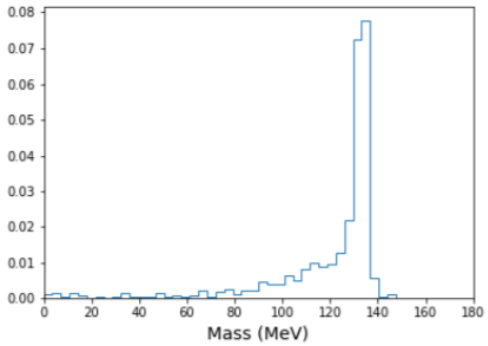
Pion multiplicity

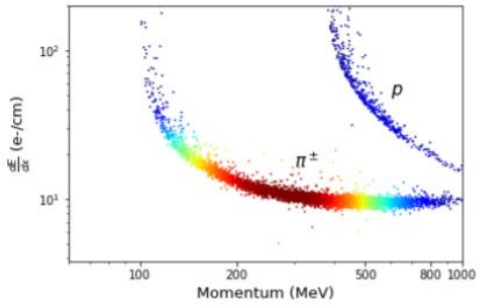


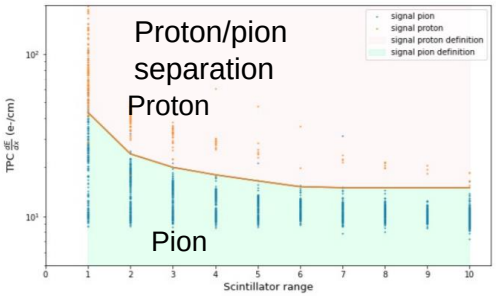
Event timing



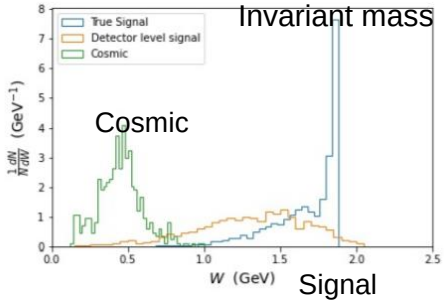
π^0 mass reconstruction







Invariant mass



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

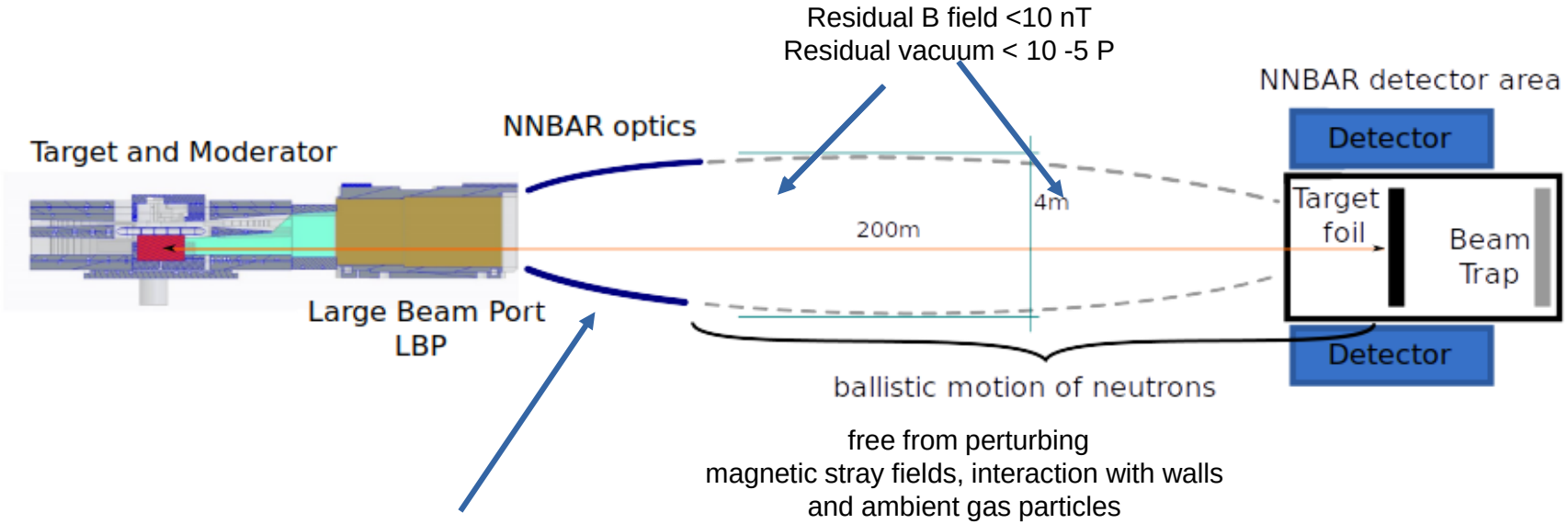
Article

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

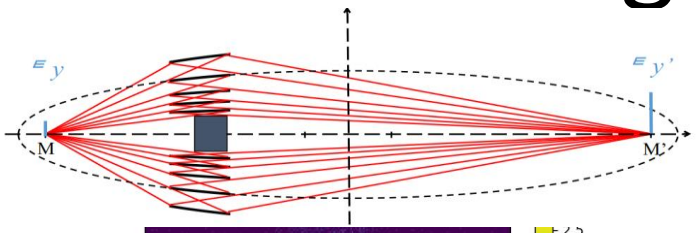
NNBAR Experiment



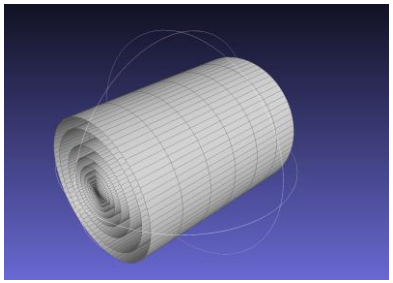
free from perturbing
magnetic stray fields, interaction with walls
and ambient gas particles

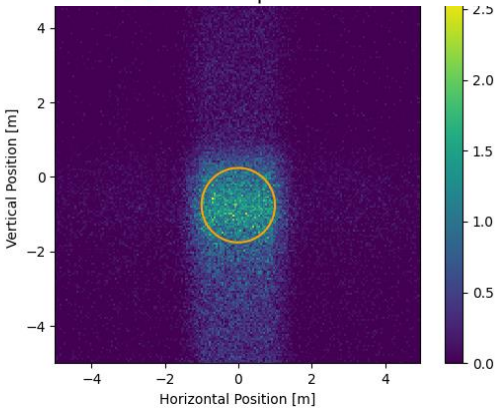
Reflector Optics
collect large solid angle of emitted neutrons and re-focus to detector area

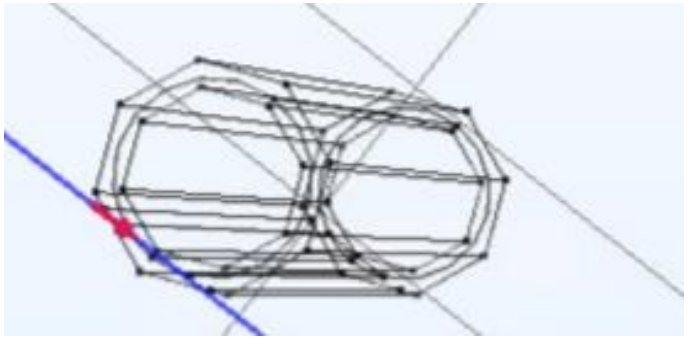
Optics and magnetic shielding

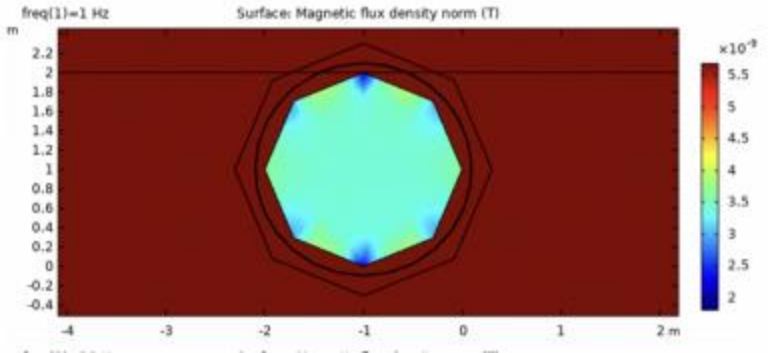


Nested Reflector
McStas simulation
Sensitivity per year
~”250 ILL units”









Outer + inner octagon shield from mu-metal

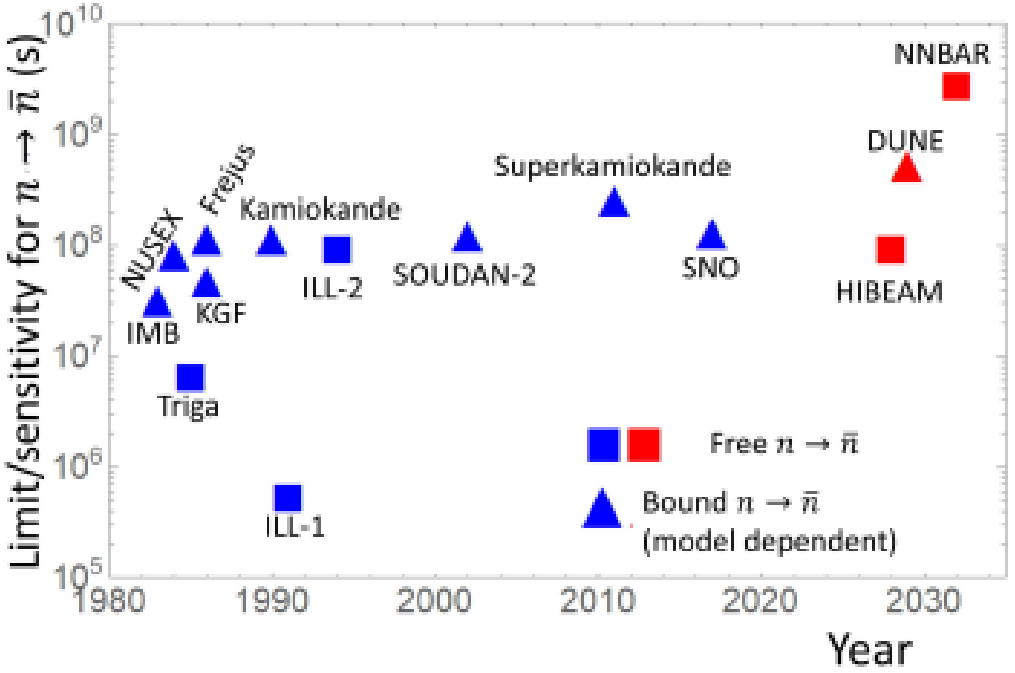
Round steel vacuum chamber: between shields

COMSOL simulations

<10 nT

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.



HIBEAM/NNBAR

- Developed from an Expression of Interest for a $n \to \bar{n}$ 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]

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[f]*Indiana University Quantum Science and Engineering Center, Bloomington, IN 47408, USA*
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- 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

- Baryon number violation not occurring in Nature would be the surprise
- Conversion of beam neutrons to sterile neutrons and/or antineutrons is a high sensitivity and clean means of searching for $\Delta B = 1,2$ with other hitherto conserved quantities unviolated.
- The ESS opens a new discovery window
- Sensitivity improvements of x10 ($n \rightarrow n'$) and x1000 ($n \rightarrow \bar{n}$) possible.
- Multistage program of HIBEAM/NNBAR planned
- Cross-disciplinary community – neutronics, magnetics, detector specialists
- Support from Swedish and EU funding agencies
- Next step CDR's!
- Much to do and more collaborators are **always** welcome !!

Kunskap är en bättre gåva än allt guld som glimmar