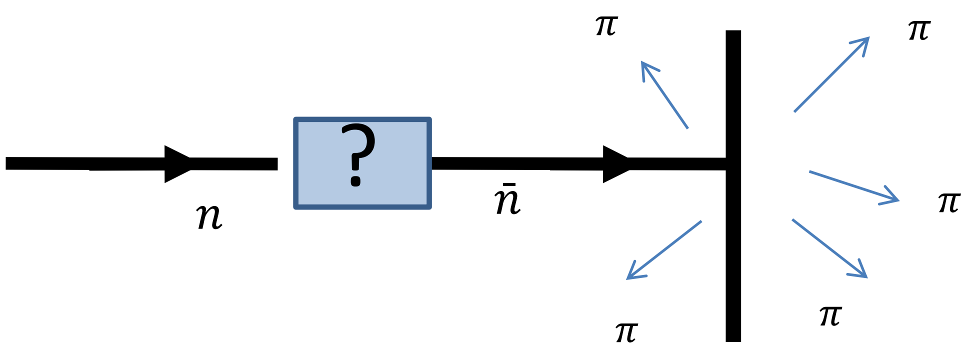
Hunting the missing baryon number violation at the ESS



D. Milstead
Stockholm University

Outline

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

Baryon and lepton number violation

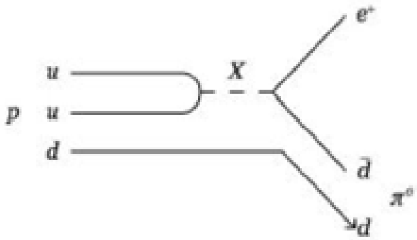
- *BN,LN* "accidental" SM symmetries at perturbative level
  - *BNV, LNV* in SM non-perturbatively (eg sphalerons)
  - *B-L* is conserved, not *B*, *L* separately.
- *BNV* needed for baryogenesis (Sakharov condition)
- *BNV,LNV* generic features of SM extensions (eg SUSY)

- Need to explore the possible selection rules:

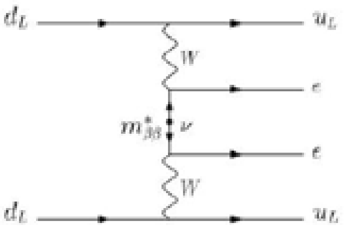
$$\Delta B \neq 0\,, \Delta L = 0, \Delta[B-L] \neq 0$$
$$\Delta B = 0\,, \Delta L \neq 0, \Delta[B-L] \neq 0$$
$$\Delta L \neq 0\,,\ \Delta B \neq 0, \Delta[B-L] = 0$$

.....

BNV,LNV selection rules

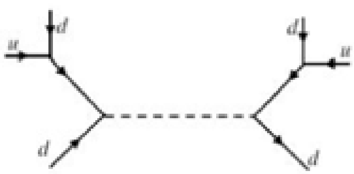


$$p \to e^+ + \pi^0$$
$$\Delta B \neq 0, \Delta L \neq 0$$

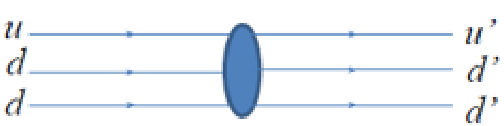


$$0\nu 2\beta$$
$$\Delta B = 0, \Delta L \neq 0$$

Left-right symmetric models ($n\bar{n}$, $0\nu 2\beta$)



$$n \to \bar{n}$$
$$\Delta B = 2, \Delta L = 0$$



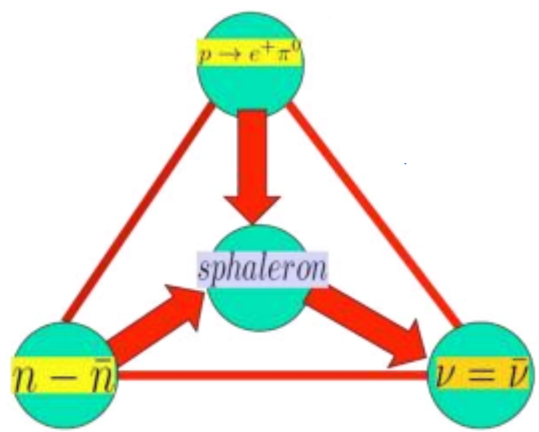
$n \to n'$ (mirror)
$$\Delta B = 1, \Delta L = 0$$

Supersymmetry (RPV)
Unification models: $M \sim 10^{15}$ GeV
Extra dimensions
Post-sphaleron baryogenesis
Dark sector
……

BSM processes combine in the SM

Symbiosis in the Standard Model between

- Proton decay, neutrinoless double beta decay, and $n \to \bar{n}$
- Electroweak sphaleron process:
  - QQQQQQ QQQL LL~ $(p \to e + \pi)$ $\times(n \to \bar{n})$ $\times(\upsilon \to \bar{\upsilon})$



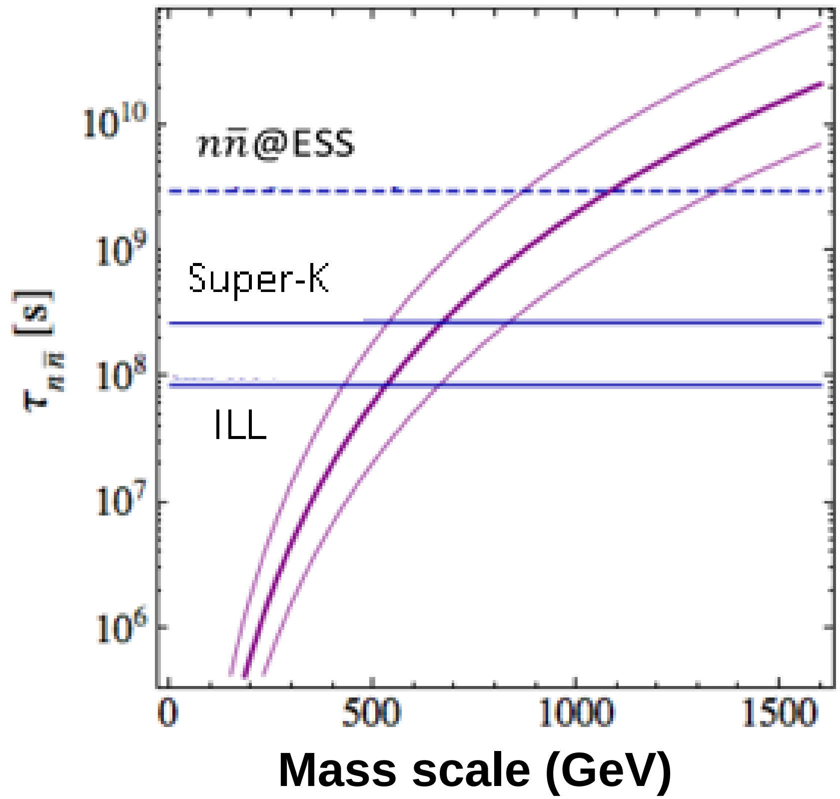
Observation of two processes implies the existence of the other one.

Mass scale for new physcs from dimensional arguments

Basic EFT approach

Dimension nine operator $\mathcal{O} \sim \frac{(qdd)^2}{\Lambda^5}$

Probe PeV scale with a search for $n \rightarrow \bar{n}$ at the European Spallation Source



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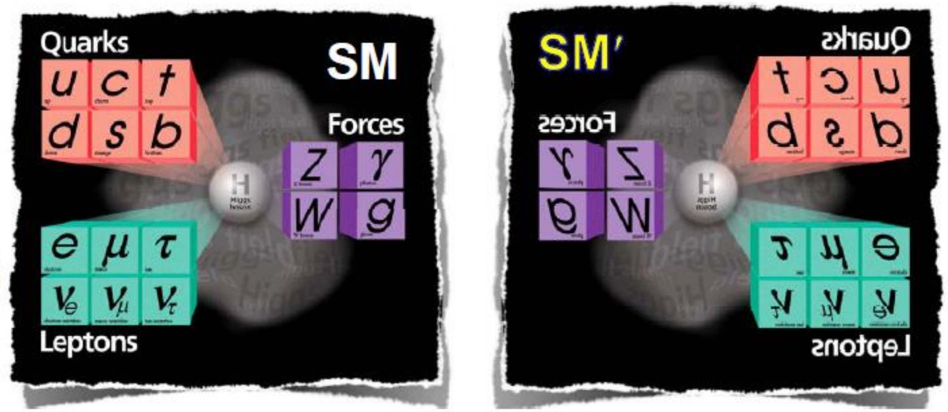
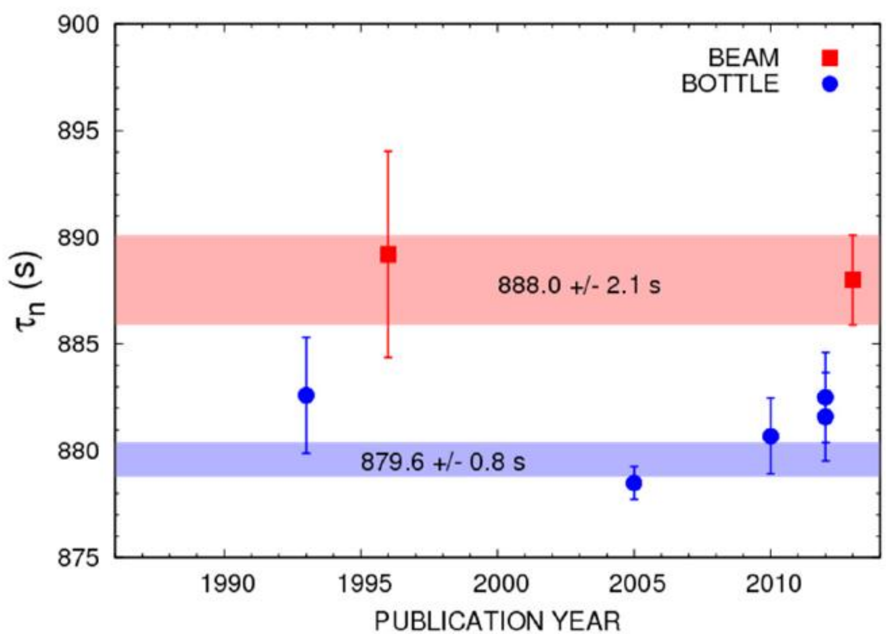
Mirror neutrons

"Hidden/mirror" sector
Restores parity symmetry.
Possible mixing for $Q = 0$ particles, eg, $n \to n'$
Mirror matter : dark matter candidates (m< 10 GeV)



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



An experimentalist's view

Forgetting theory...

A blue sky search for BNV → process in which only baryon number is violated.

(RPP)

Decay mode	Partial mean life ($\times 10^{30}$ yrs)
$N \to e^+ \pi$	> 2000 (n), > 8200 (p)
$N \to \mu^+ \pi$	> 1000 (n), > 6600 (p)
$N \to \nu \pi$	> 1100 (n), > 390 (p)
$p \to e^+ \eta$	> 4200
$p \to \mu^+ \eta$	> 1300
$n \to \nu \eta$	> 158
$N \to e^+ \rho$	> 217 (n), > 710 (p)
$N \to \mu^+ \rho$	> 228 (n), > 160 (p)
$N \to \nu \rho$	> 19 (n), > 162 (p)
$p \to e^+ \omega$	> 320
$p \to \mu^+ \omega$	> 780
$n \to \nu \omega$	> 108
$N \to e^+ K$	> 17 (n), > 1000 (p)
$N \to \mu^+ K$	> 26 (n), > 1600 (p)
$N \to \nu K$	> 86 (n), > 5900 (p)
$n \to \nu K^0_S$	> 260
$p \to e^+ K^*(892)^0$	> 84
$N \to \nu K^*(892)$	> 78 (n), > 51 (p)
$p \to e^+ \pi^+ \pi^-$	> 82
$p \to e^+ \pi^0 \pi^0$	> 147
$n \to e^+ \pi^- \pi^0$	> 52
$p \to \mu^+ \pi^+ \pi^-$	> 133
$p \to \mu^+ \pi^0 \pi^0$	> 101
$n \to \mu^+ \pi^- \pi^0$	> 74
$n \to e^+ K^0 \pi^-$	> 18
$n \to e^- \pi^+$	> 65
$n \to \mu^- \pi^+$	> 49
$n \to e^- \rho^+$	> 62
$n \to \mu^- \rho^+$	> 7
$n \to e^- K^+$	> 32
$n \to \mu^- K^+$	> 57
$p \to e^- \pi^+ \pi^+$	> 30
$n \to e^- \pi^+ \pi^0$	> 29
$p \to \mu^- \pi^+ \pi^+$	> 17
$n \to \mu^- \pi^+ \pi^0$	> 34
$p \to e^- \pi^+ K^+$	> 75
$p \to \mu^- \pi^+ K^+$	> 245

$p \to e^+ \gamma$	> 670
$p \to \mu^+ \gamma$	> 478
$n \to \nu \gamma$	> 28
$p \to e^+ \gamma\gamma$	> 100
$n \to \nu \gamma\gamma$	> 219
$p \to e^+ e^+ e^-$	> 793
$p \to e^+ \mu^+ \mu^-$	> 359
$p \to e^+ \nu \nu$	> 170
$n \to e^+ e^- \nu$	> 257
$n \to \mu^+ e^- \nu$	> 83
$n \to \mu^+ \mu^- \nu$	> 79
$p \to \mu^+ e^+ e^-$	> 529
$p \to \mu^+ \mu^+ \mu^-$	> 675
$p \to \mu^+ \nu \nu$	> 220
$p \to e^- \mu^+ \mu^+$	> 6
$n \to 3\nu$	> 0.0005
$N \to e^+$ anything	> 0.6 (n, p)
$N \to \mu^+$ anything	> 12 (n, p)
$N \to e^+ \pi^0$ anything	> 0.6 (n, p)
$pp \to \pi^+ \pi^+$	> 0.7
$pn \to \pi^+ \pi^0$	> 2
$nn \to \pi^+ \pi^-$	> 0.7
$nn \to \pi^0 \pi^0$	> 3.4
$pp \to K^+ K^+$	> 170
$pp \to e^+ e^+$	> 5.8
$pp \to e^+ \mu^+$	> 3.6
$pp \to \mu^+ \mu^+$	> 1.7
$pn \to e^+ \overline{\nu}$	> 2.8
$pn \to \mu^+ \overline{\nu}$	> 1.6
$pn \to \tau^+ \overline{\nu}_\tau$	> 1.0
$nn \to \nu_e \overline{\nu}_e$	> 1.4
$nn \to \nu_\mu \overline{\nu}_\mu$	> 1.4

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

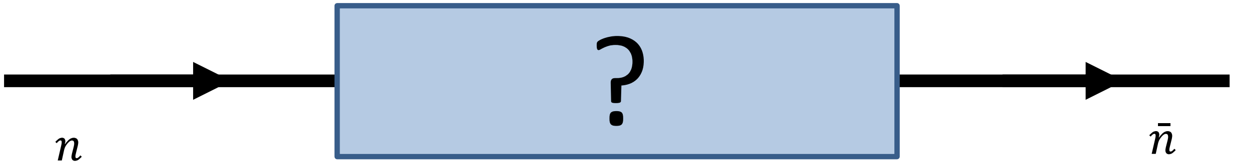
$\Delta B \neq 0, \Delta L = 0$

Few searches for $\Delta B \neq 0, \Delta L = 0$

Outline

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

$n \rightarrow \bar{n}$ mixing formalism



$$i\hbar \frac{\partial}{\partial t}\begin{pmatrix} n \\ \bar{n} \end{pmatrix} = \begin{pmatrix} E_n & \delta m \\ \delta m & E_{\bar{n}} \end{pmatrix}\begin{pmatrix} n \\ \bar{n} \end{pmatrix}$$

$\delta m = \langle \bar{n} | H_{eff} | n \rangle < 10^{-29}$ MeV $= n\bar{n}$ mixing physics

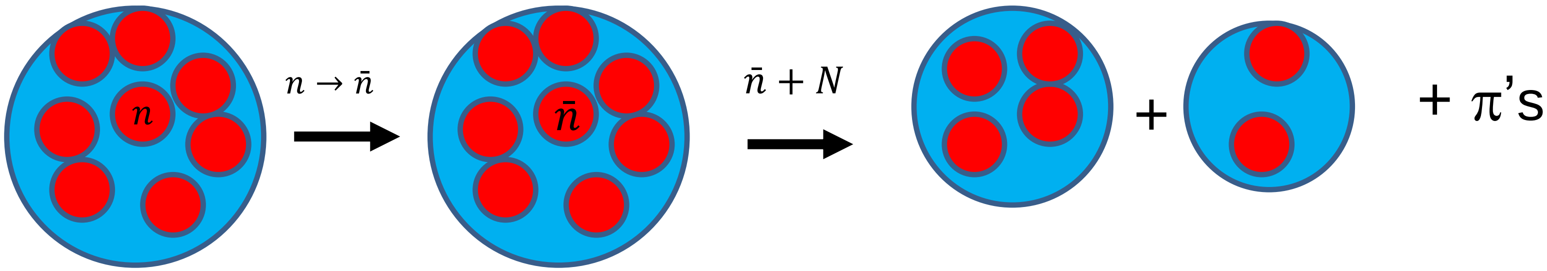
$$P_{n\rightarrow\bar{n}} = \left(\frac{\delta m}{\Delta E}\right)^2 \sin^2(\Delta E \times t) \quad ; \Delta E = E_n - E_{\bar{n}}$$

Free neutron oscillation:

- Quasi-free limit : $\Delta E t \sim 1 \Rightarrow P \sim (\delta m \times t)^2$
- Slow neutrons, propagating over a long distance

Searching with bound neutrons

Nuclear disintegration after neutron oscillation



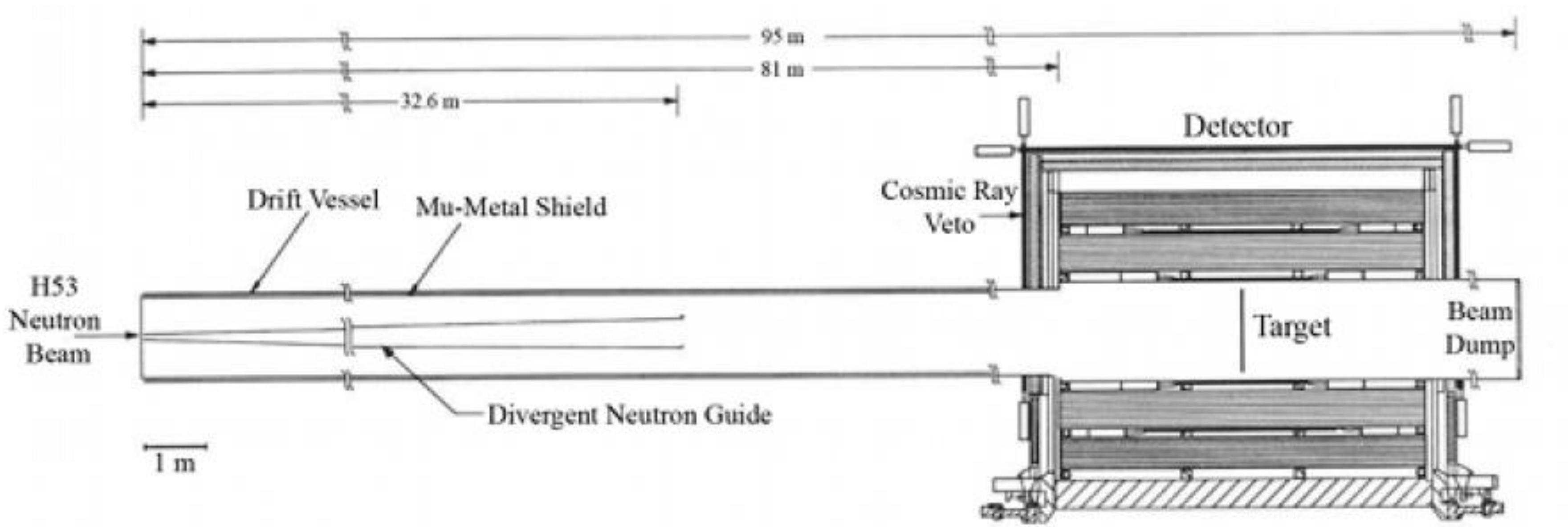
$$P_{n\to\bar{n}} = \left(\frac{\delta m}{\Delta E}\right)^2 \sin^2(\Delta E \times t) \;,$$

$\Delta E \sim 100$ MeV .

$$\Rightarrow \text{Suppression:} \left(\frac{\delta m}{\Delta E}\right)^2 < 10^{-60}$$

Best current limits (SuperKamiokande) $\Rightarrow$ $\tau_{free} > 4.7 \times 10^8$ s
Irreducible bg's prevent large improvements.
Model−dependent (nuclear interactions).

Free neutron search at ILL



Institute Laue−Langevin (Early 1990′s).
Cold neutron beam from 58MW reactor.
$\sim 130\mu$m thick carbon target
100m propagation in field-free region

Signal of at least two tracks with $E > 850$ MeV
0 candidate events, 0 background.
$\Rightarrow \tau_{n\to\bar{n}} > 0.86 \times 10^8$s.

Outline

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

The European Spallation Source

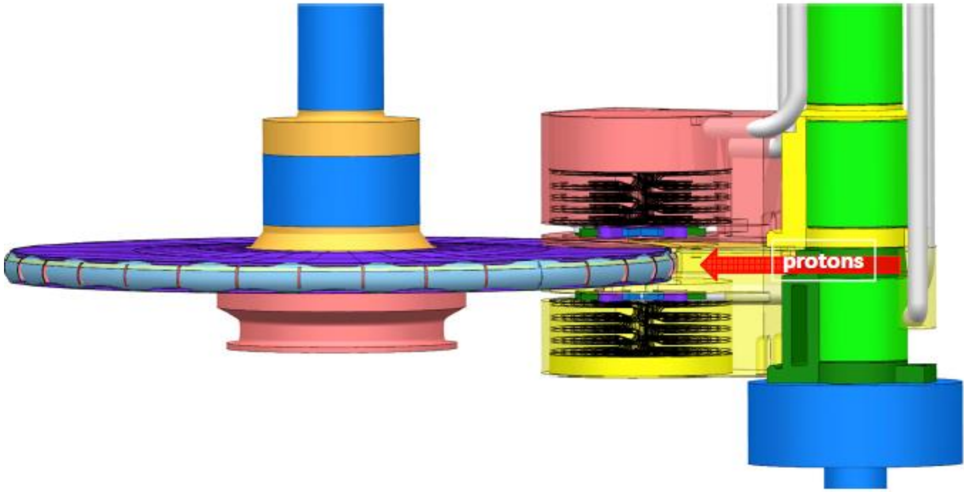
High intensity spallation neutron source

Multidisplinary research centre with 17 European nations participating.

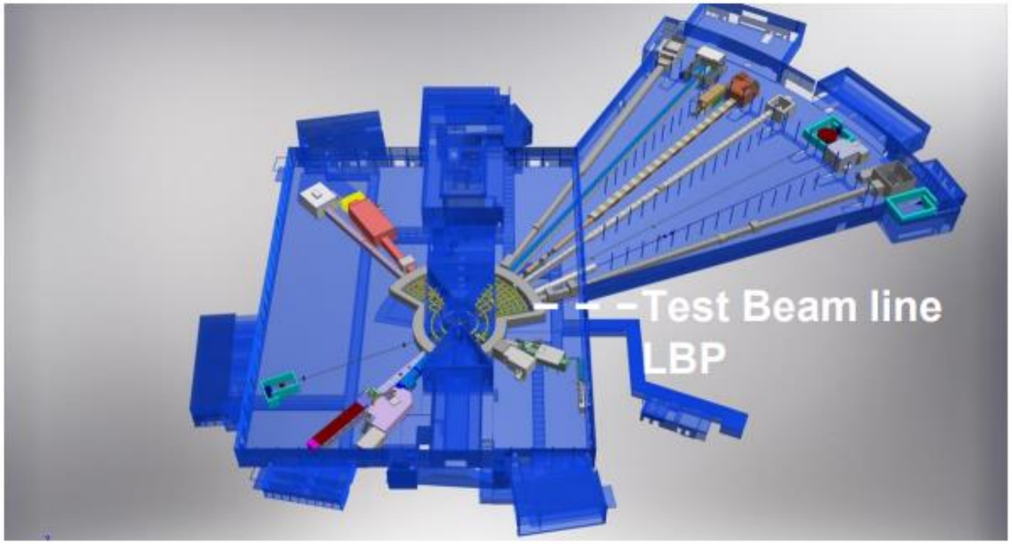
Lund, Sweden.
Start operations in 2023/2024.

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

Cold neutrons after interaction with moderators.



Beamlines and program



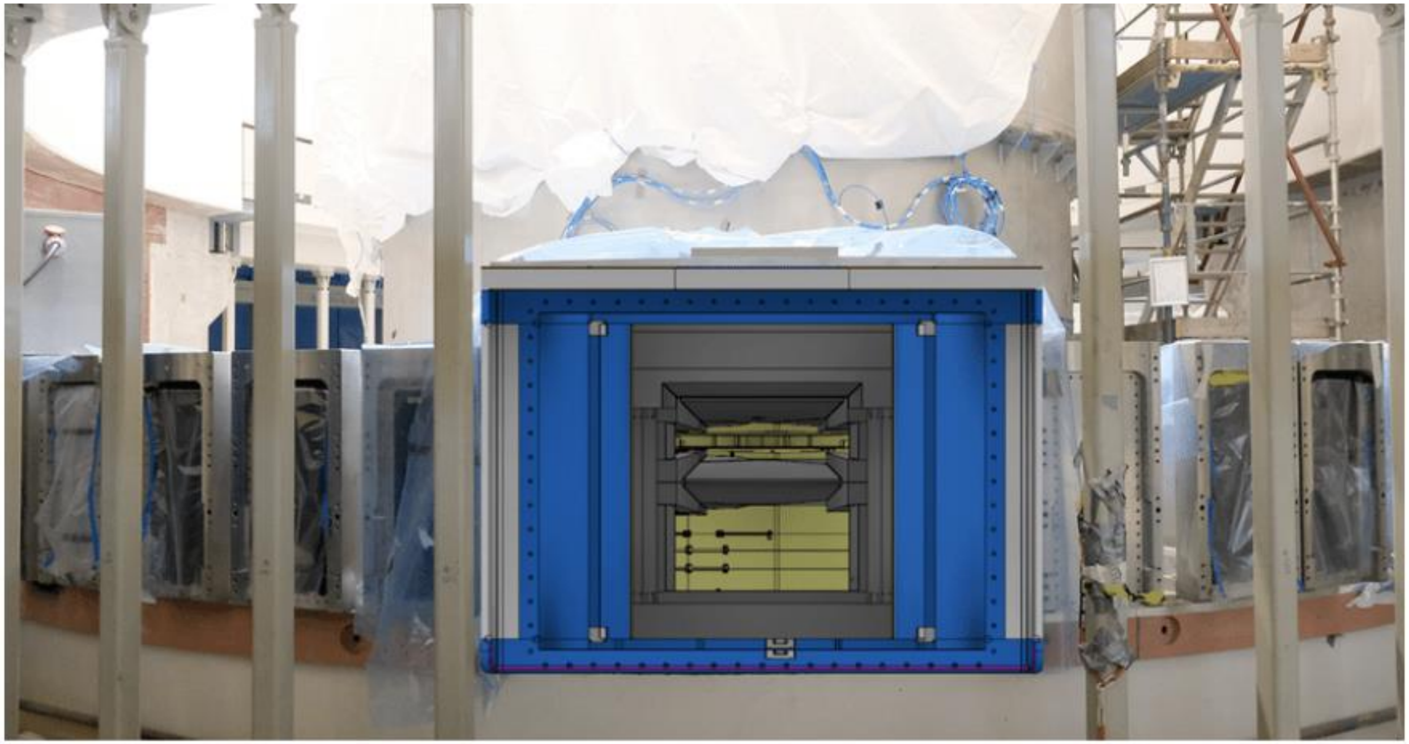
R&D
Annihilation detector prototype
Conceptual design reports for HIBEAM/NNBAR

TDRs and small scale experiment at ESS test beamline

HIBEAM
High precision induced:
$n \to n'$, $n \to \bar{n}$ (x10 improvement)
First search for free $n \to \bar{n}$ at a spallation source
Eg at upgraded test beamline

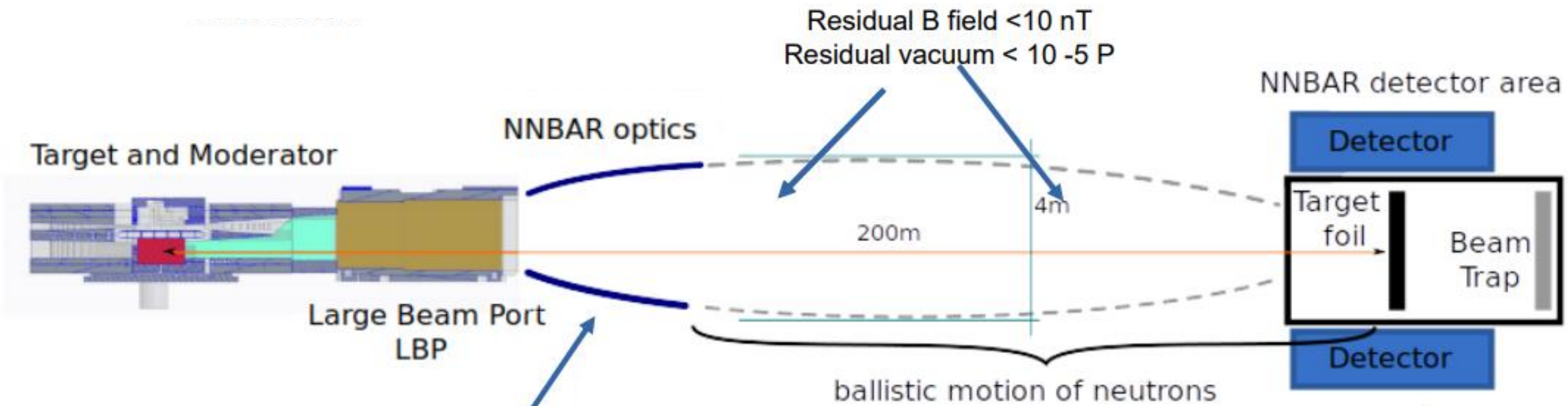
NNBAR
High sensitivity free $n \to \bar{n}$ (x1000 improvement)
At the Large Beam Port

NNBAR – start the Large Beam Port



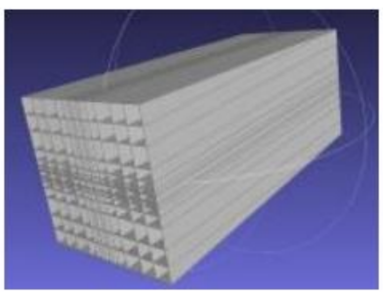
Photograph of the frame of the Large Beam Port being installed in the ESS monolith. A superimposed CAD drawing is showing the field of view of the LBP. The upper moderator, the inner shielding to avoid a direct view of the target, and the space below the target where the high-intensity moderator will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

The NNBAR Experiment

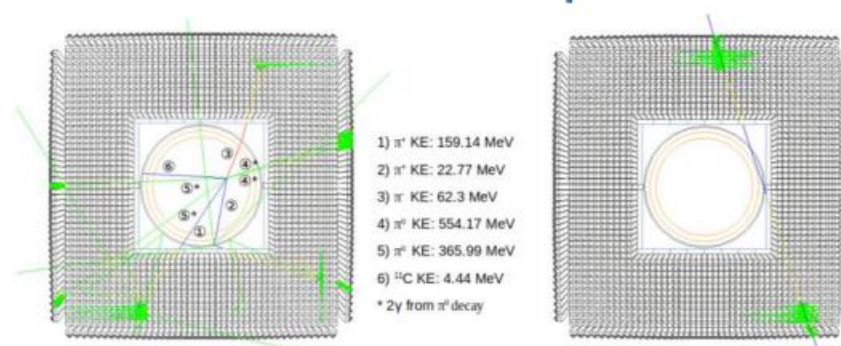


free from perturbing
magnetic stray fields, interaction with walls
and ambient gas particles

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



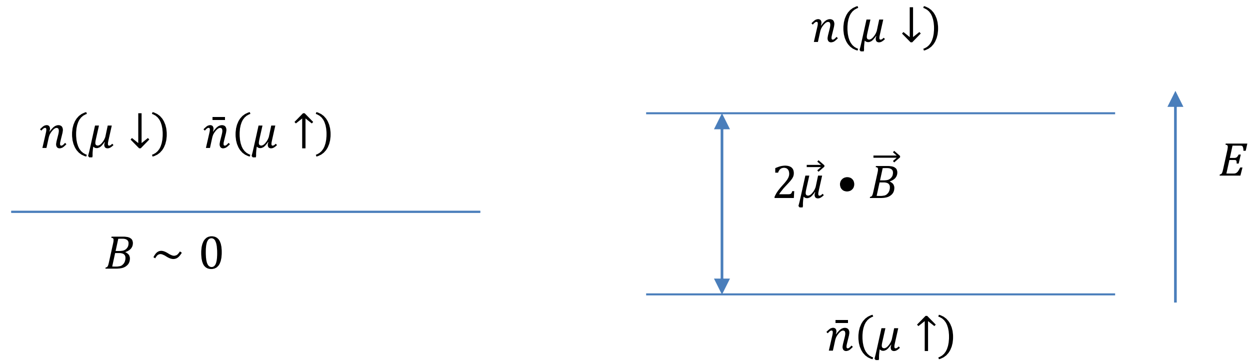
Eg double planar reflector



TPC + scintillators and lead-glass

Multi-disciplinary environment needed.

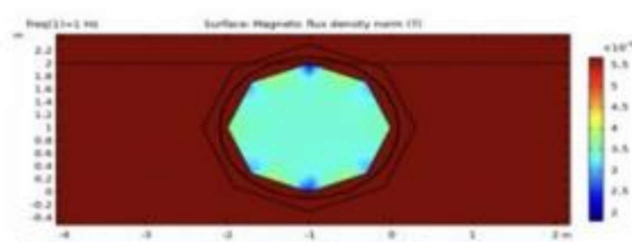
The need for magnetic shielding



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

Flight time ≤ 1s
For quasi−free condition $\Delta E \times t \ll 1$
$\Rightarrow B \leq 10$nT and vacuum $\leq 10^{-5}$ Pa.

Outer and inner octagon-shaped passive shield of 1-2 mm thick sheets of mumetal.

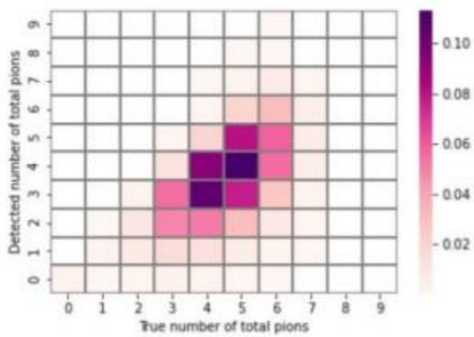


COMSOL

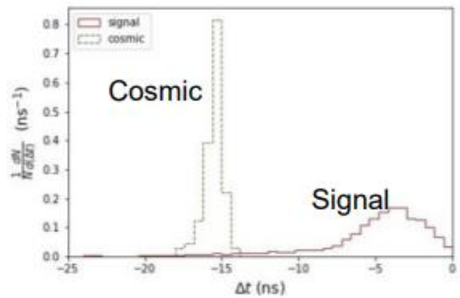
Residual B field <10 nT

Geant-4 detector simulation

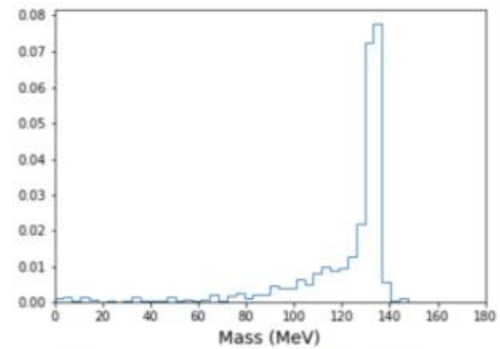
Pion multiplicity

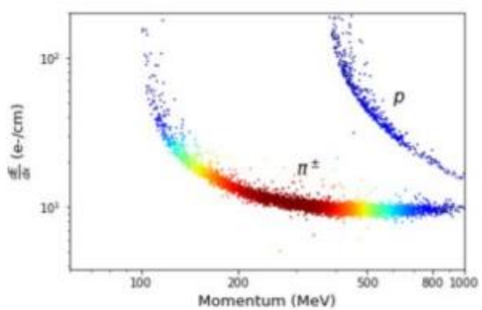


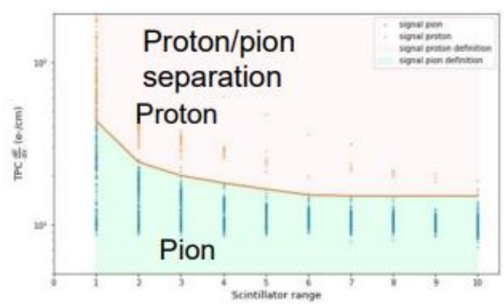
Event timing

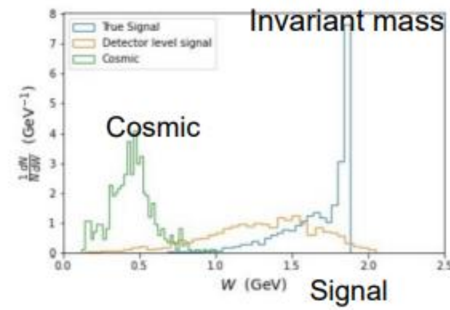


π^0 mass reconstruction









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

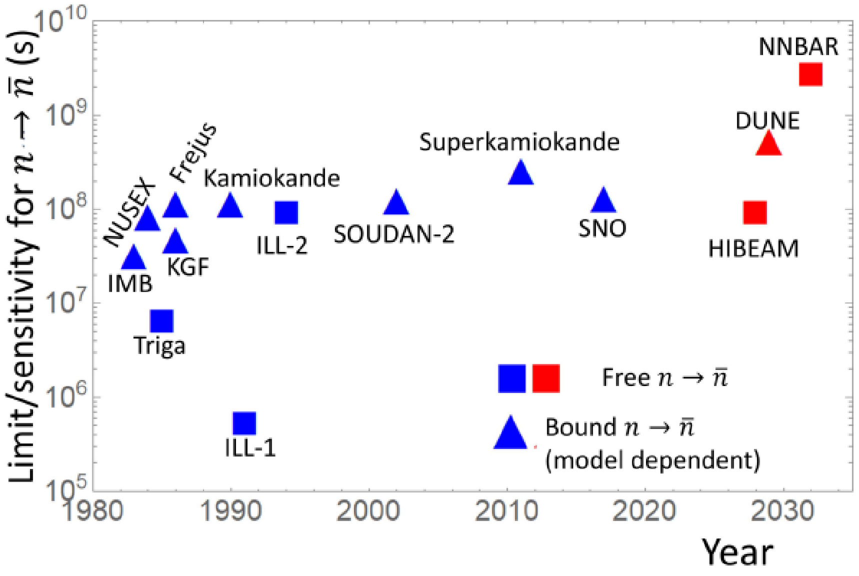
Backgrounds

- 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.

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



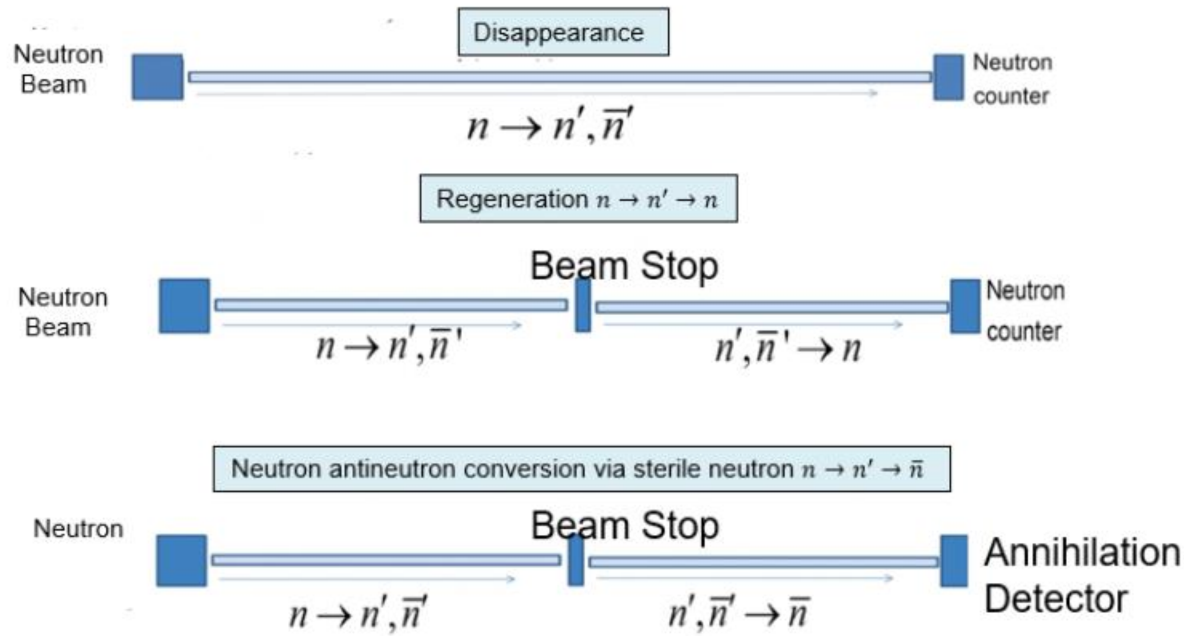
Increase in sensitivity for $P_{n\bar{n}} \sim 10^3$ compared to previous experiment (ILL)
Stability of matter (τ_{life}) sensitivity $\sim 10^{35}$yrs
Discovery or new stringent limit on models of new physics and stability of matter.

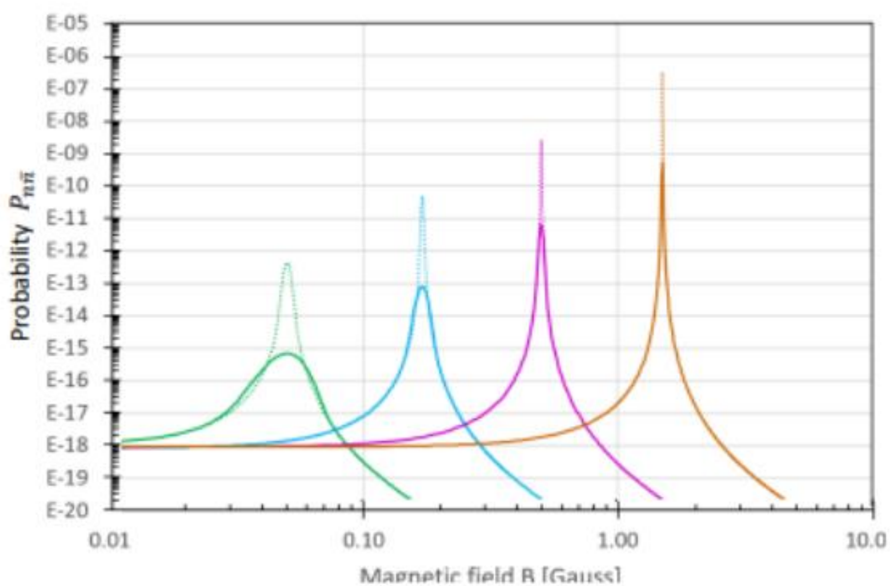
HIBEAM

Search for sterile neutron oscillations at HIBEAM

Complementary suite of searches to constrain mixing Hamiltonian

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





Explore disappearance, regeneration and induced $n \to n'$

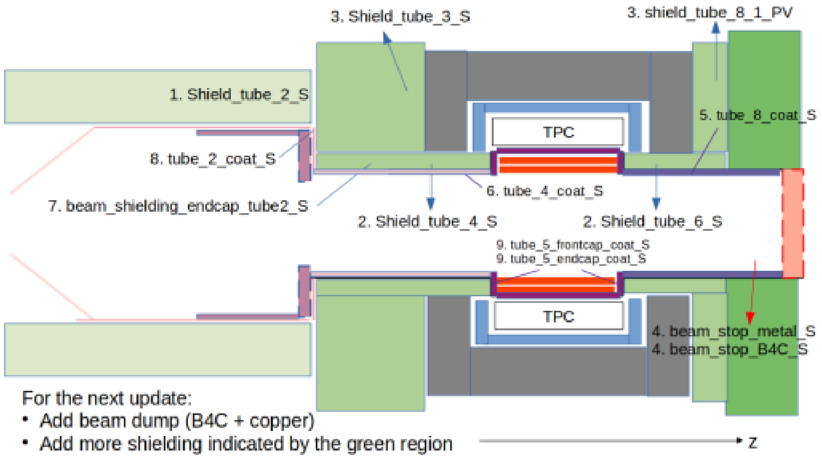
Use custom annihilation detector and WASA CsI (Na) crystal calorimeter for the annihilation detector

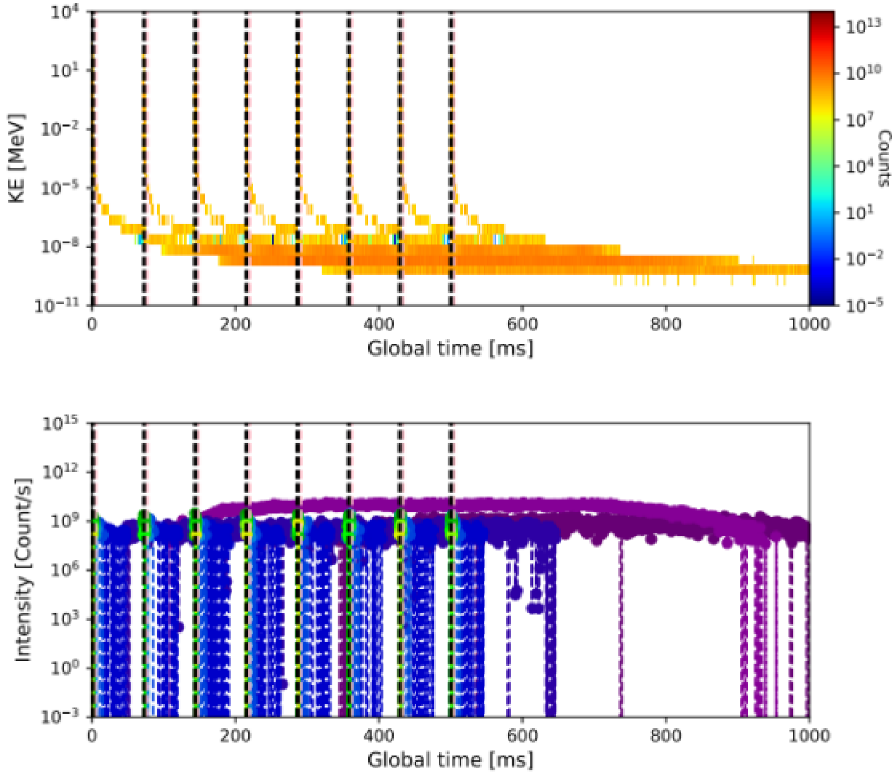
Extend sensitivity in oscillation time by x 100

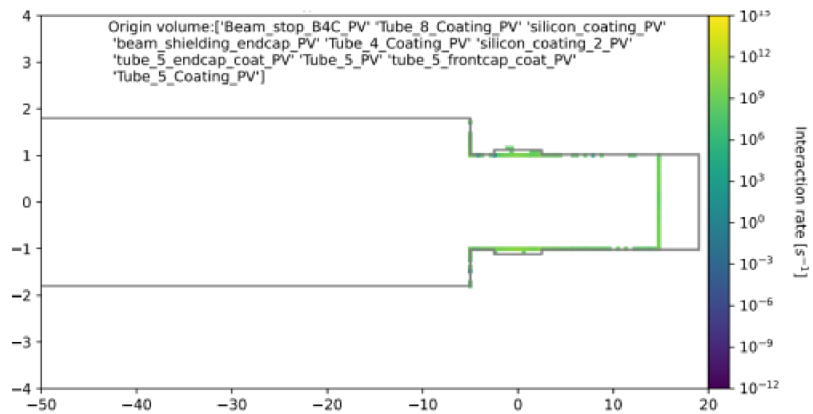
Pilot experiment for free $n \longrightarrow \bar{n}$

NNBAR to have pile-up background from, eg 10^9 photons/s

Measurements of spallation backgrounds and benchmark of simulations



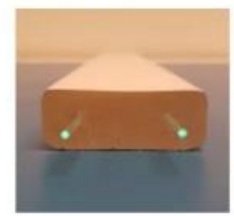


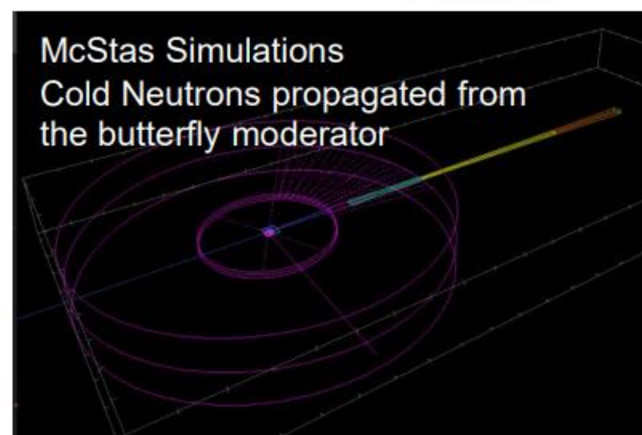


Beamline available – can beat the previous ILL sensitivity by factor x10

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





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

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

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

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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

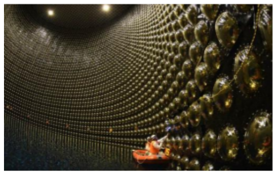
- Neutron oscillations are a key but rarely explored portal for new physics
  - baryogenesis, BSM physics, dark matter
- The ESS is opening a new discovery window
- HIBEAM/NNBAR is a multidisciplinary program to increase sensitivity by ~1000
- Such a leap in sensitivity in tests of a global symmetry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

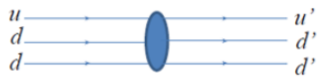
A. The quest for dark matter and the exploration of flavour and fundamental symmetries are crucial components of the search for new physics. This search can be done in many ways, for example through precision measurements of flavour physics and electric or magnetic dipole moments, and searches for axions, 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.***

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

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

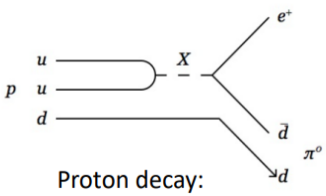
Fitting into the European landscape



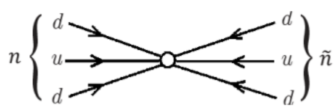


Neutron-sterile neutron:
$n \longrightarrow n', \Delta B = 1, \Delta L = 0$

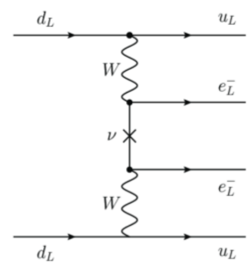
Relatively unexplored selection rules HIBEAM/NNBAR



Proton decay:
$p \longrightarrow \ell + meson$
$\Delta B = 1, \Delta L = 1$



Neutron-antineutron:
$n \longrightarrow \bar{n}$
$\Delta B = 2, \Delta L = 0$



Neutrinoless double beta decay, $0\nu 2\beta$
$\Delta B = 0, \Delta L = 2$

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.***