Hunting the missing baryon number violation and beyond at the ESS

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Outline

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

Particle physics today in one slide

- The Standard Model is complete
- Neutrino masses are not understood.
- Other outstanding problems remain e.g. baryogenesis, dark matter…
- The LHC has arguably given the most important scientific result of the century (so far).
- Discoveries of fundamental importance are no longer assured (nor are they excluded) by exploring at higher collision energy.
- **A strong need for a diverse field.**

Baryon and lepton number violation

- BN, LN "accidental" SM symmetries at perturbative level
  - BNV, LNV in SM non-perturbatively (eg instantons)
  - BNV Sakharov condition for baryogenesis
- BNV, LNV generic features of SM extensions
- Need to explore the possible selection rules:

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

.....

An experimentalist's view

Decay mode Partial mean life ($\times 10^{30}$ yrs)

(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

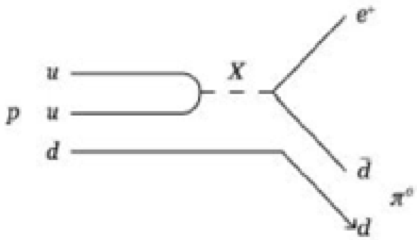
Decay mode	Partial mean life ($\times 10^{30}$ yrs)
$p \to e^+\gamma$	> 670
$p \to \mu^+\gamma$	> 478
$n \to \nu\gamma$	> 28
$p \to e^+\gamma\gamma$	> 100
$n \to \nu\gamma\gamma$	> 219
$p \to e^+e^+e^-$	> 793
$p \to e^+\mu^+\mu^-$	> 359
$p \to e^+\nu\nu$	> 170
$n \to e^+e^-\nu$	> 257
$n \to \mu^+e^-\nu$	> 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

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

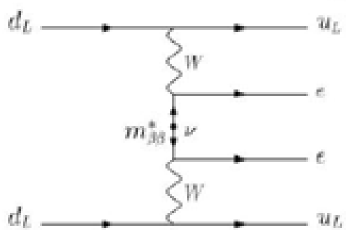
$\Delta B \neq 0, \Delta L = 0$

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

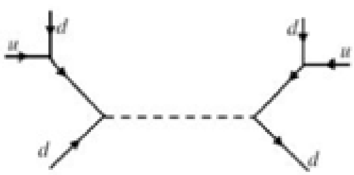
Candidate BNV,LNV processes



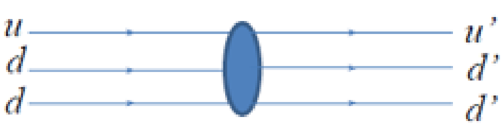
$$p \to e^{+} + \pi^{0}$$
$$\Delta B \neq 0, \Delta L \neq 0$$



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



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



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

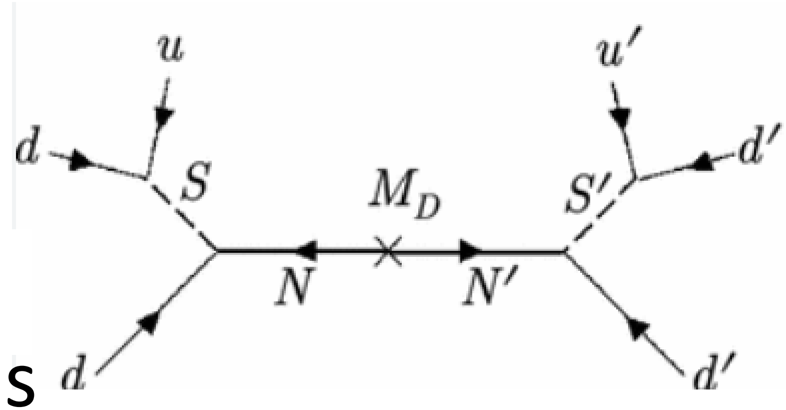
Electroweak sphaleron process:
QQQQQQ QQQL LL
~
$(p \to e + \pi) \times (n \to \bar{n}) \times (0\nu 2\beta)$

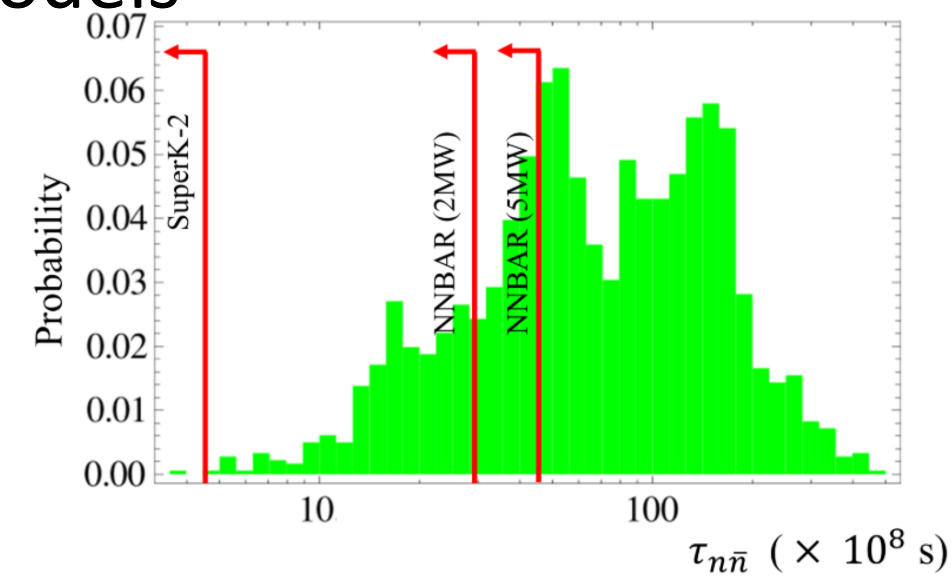
Unification models
Supersymmetry
Extra dimensions
Post-sphaleron baryogenesis
Hidden sector
……

Neutron oscillations are a key part of the landscape of new physics
Symbiosis with other processes

Neutron-antineutron oscillations

- R-parity violating supersymmetry
- Extra dimensions
- Post-sphaleron baryogenesis
- Left-right symmetric models
- etc. etc.



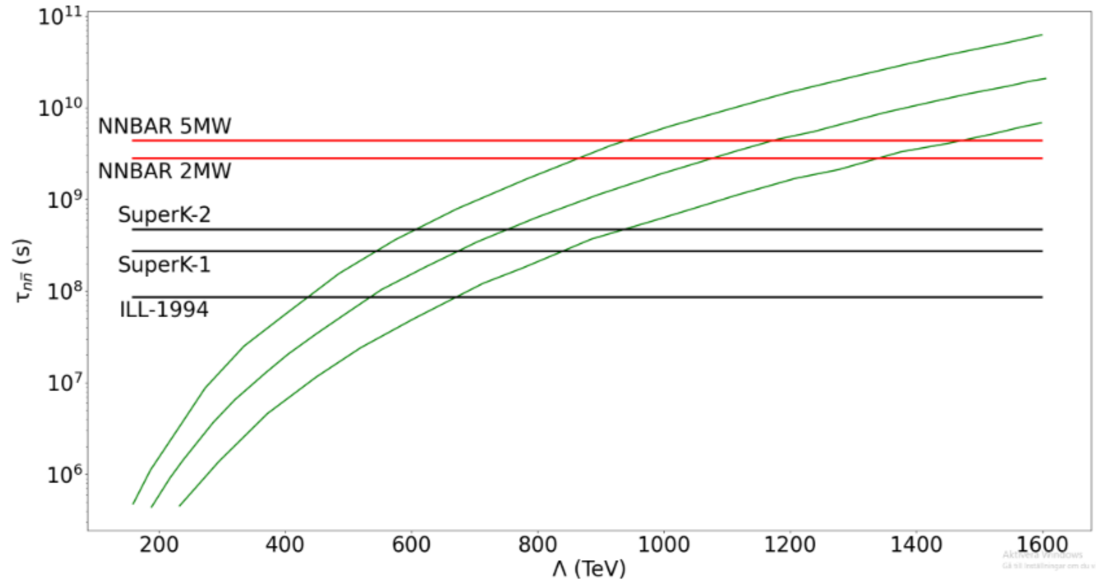


Energy scale of new physics for $n \rightarrow \bar{n}$?

Simple EFT approach
Dimension 9 (6 quark) operator

$$\mathscr{O}_{\Delta\mathscr{B}=2} = \frac{1}{\mathscr{M}^5}(udd)^2 + \text{h.c.}$$

$$\varepsilon_{n\bar{n}} = \frac{C\Lambda_{\text{QCD}}^6}{\mathscr{M}^5}$$



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A search for $n \rightarrow \bar{n}$ probes the PeV scale for new physics.

A combination of BSM signatures in the SM

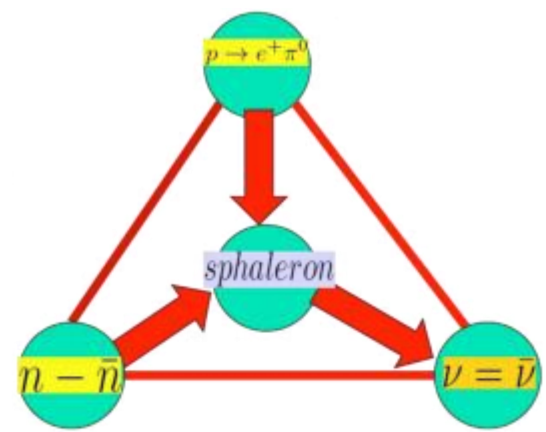
Symbiosis between proton decay, neutrinoless double beta decay and $n \to \bar{n}$ in the Standard Model:

Electroweak sphaleron process:

QQQQQQ QQQL LL

~

$(p \to e + \pi) \times (n \to \bar{n}) \times (0\upsilon 2\beta)$



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

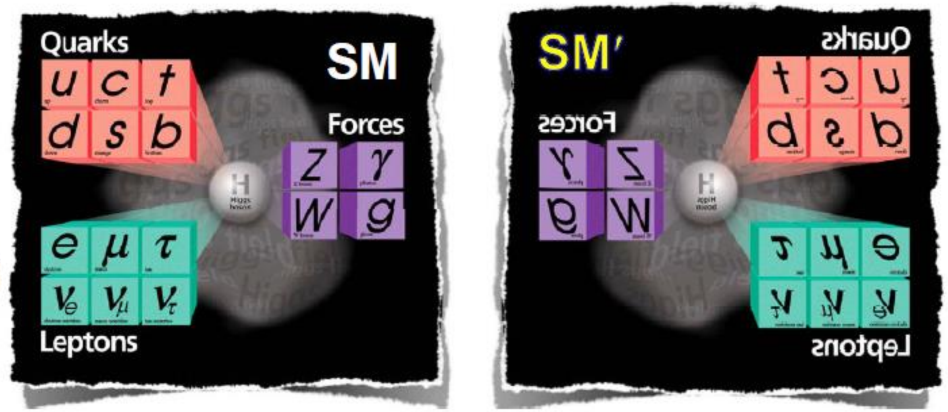
Sterile neutrons

"Hidden/mirror" sector

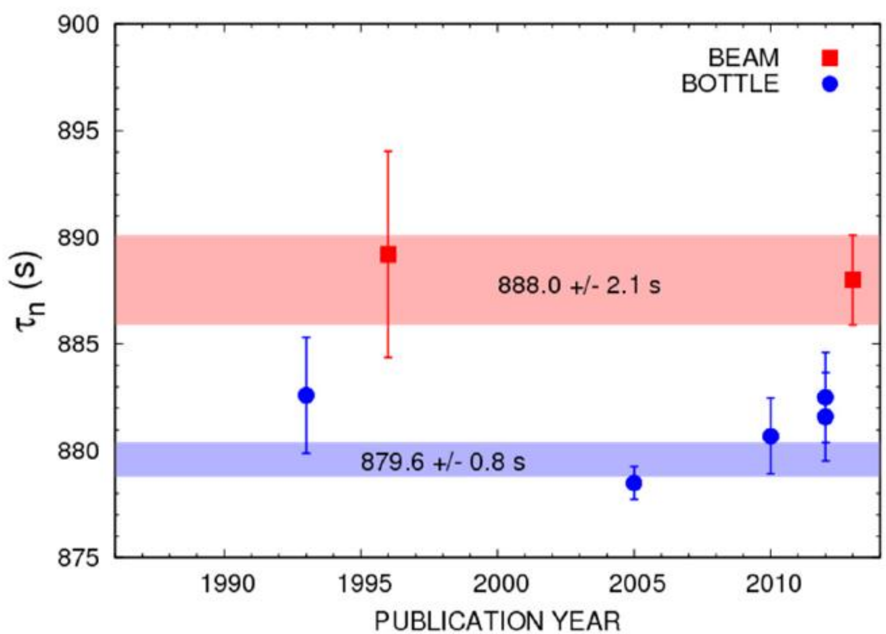
Restores parity symmetry.

Possible mixing for $Q = 0$ particles, eg, $n \to n'$

Mirror matter : dark matter candidates (m< 10 GeV)



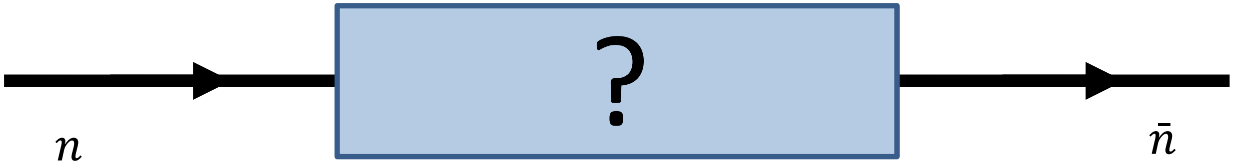
Can explain 5σ neutron lifetime discrepancy seen in bottle and beam experiments.



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

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

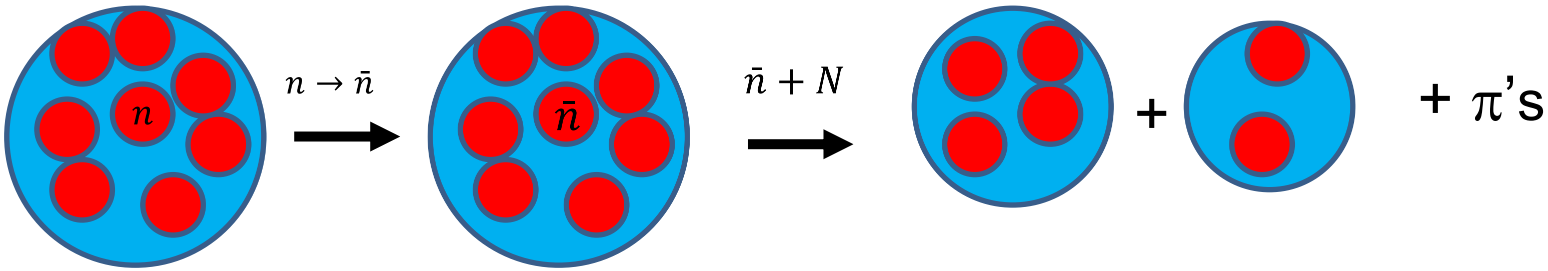
Two interesting cases:

- Free neutron oscillation: $\Delta E \times t \ll 1 \Rightarrow P \sim (\delta m \times t)^2$
- Bound neutron oscillation: $\Delta E \times t \gg 1$

Quasi-free limit : $\Delta E t \sim 1 \;\Rightarrow P \sim (\delta m \times t)^2$

Searching with bound neutrons

Nuclear disintegration after neutron oscillation



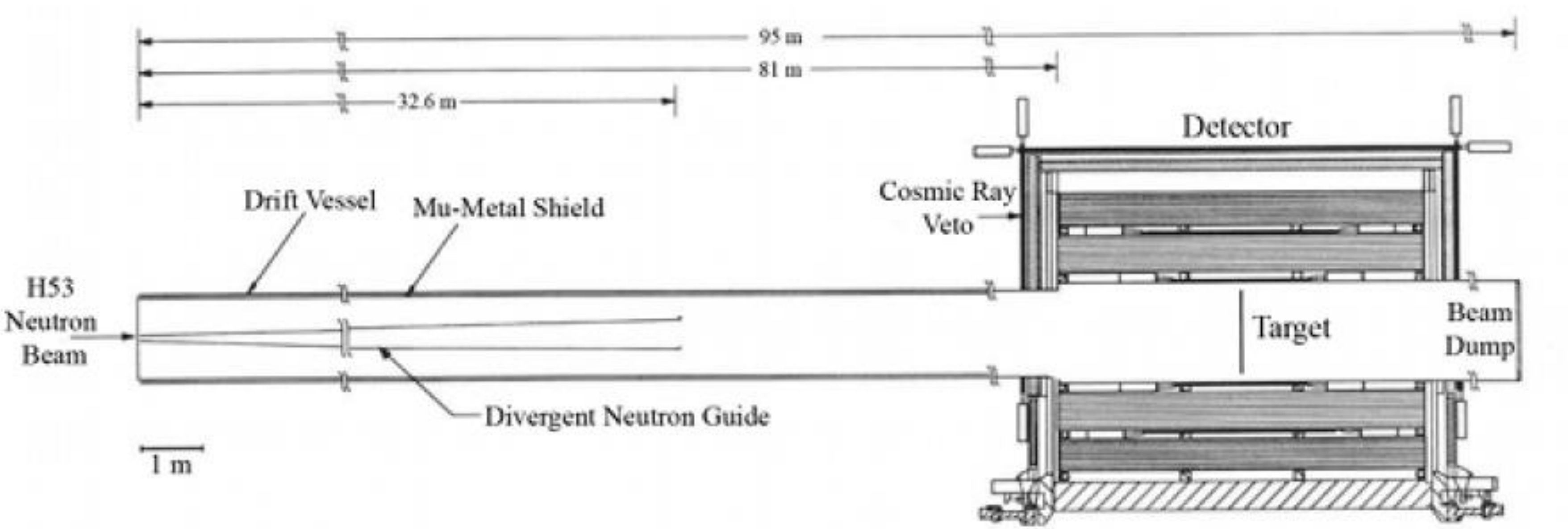
$$P_{n\to\bar{n}} = \left(\frac{\delta m}{\Delta E}\right)^2 \sin^2(\Delta E \times t) \ ,$$

$$\Delta E \sim 10 - 100 \text{ MeV} .$$

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

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

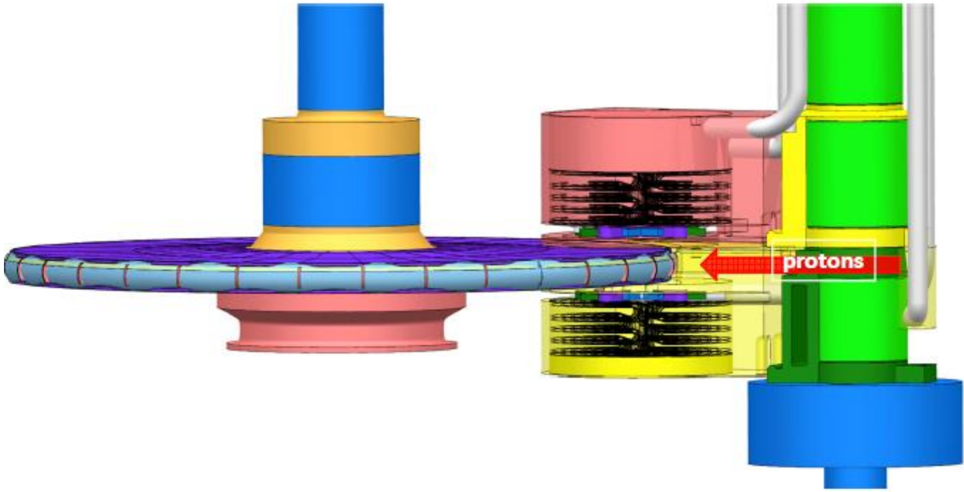
High intensity spallation neutron source

Multidisplinary research centre with 17 European nations participating.

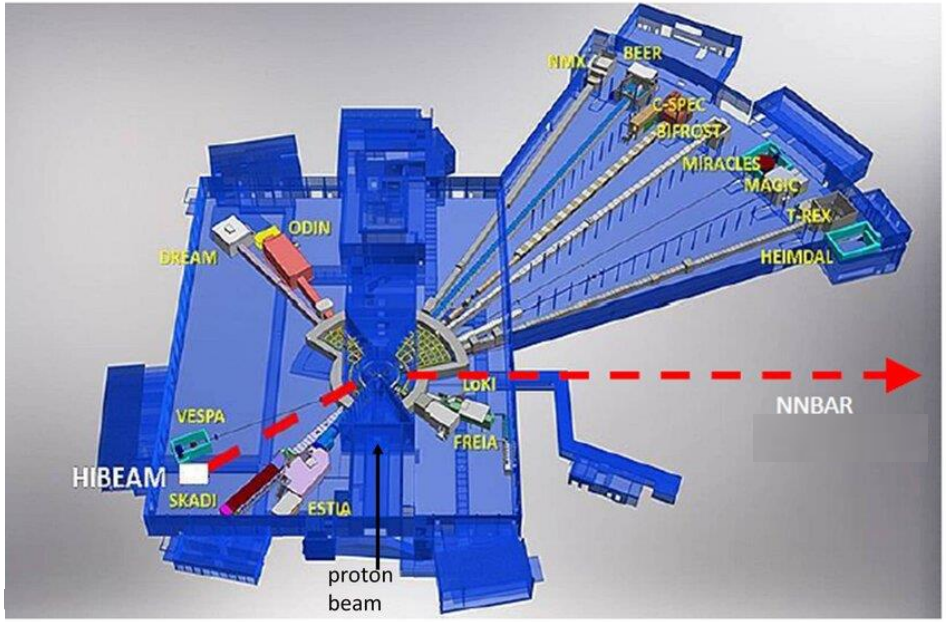
Lund, Sweden.
Start operations in 2027/2028.

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

Cold neutrons after interaction with moderators.
15 beamlines/instruments – none are Swedish-led



Beamlines and program



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

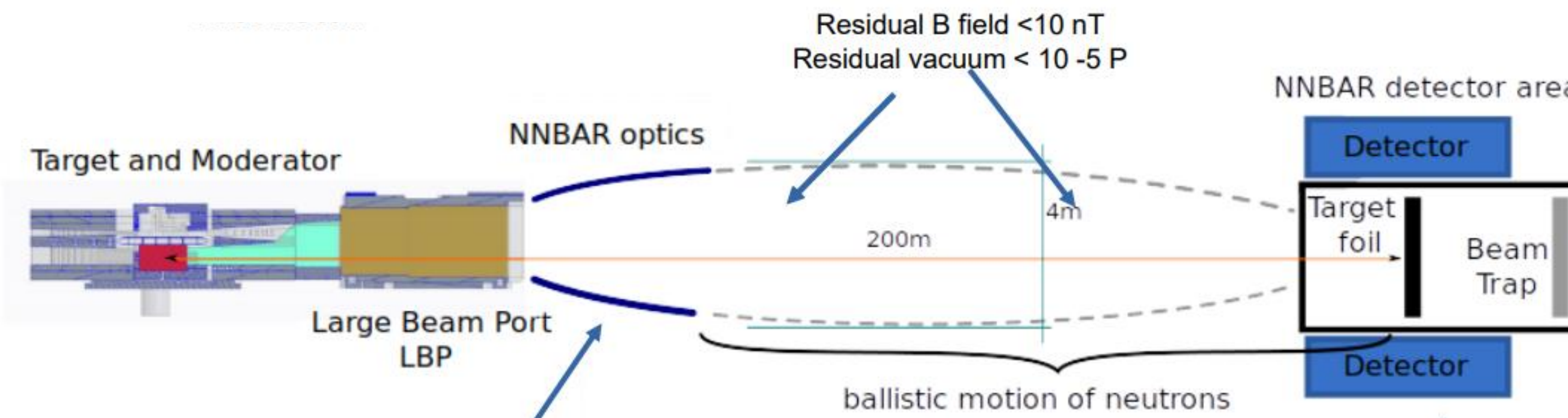
TDRs and small scale experiment

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

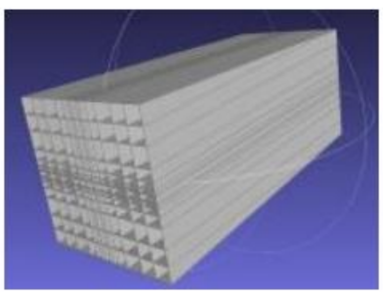
NNBAR

The NNBAR Experiment

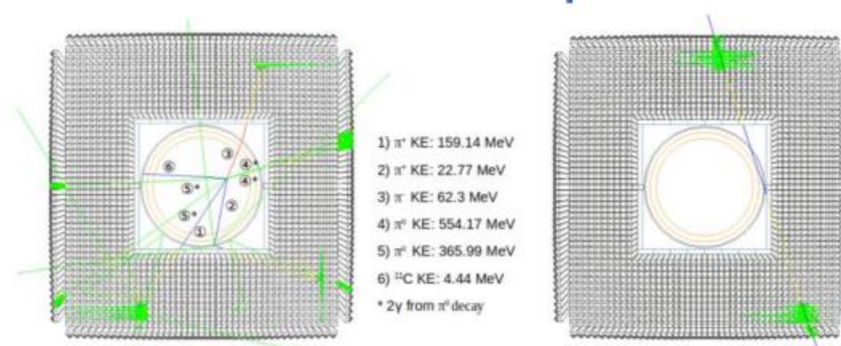


free from perturbing magnetic stray fields, interaction with walls and ambient gas particles

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

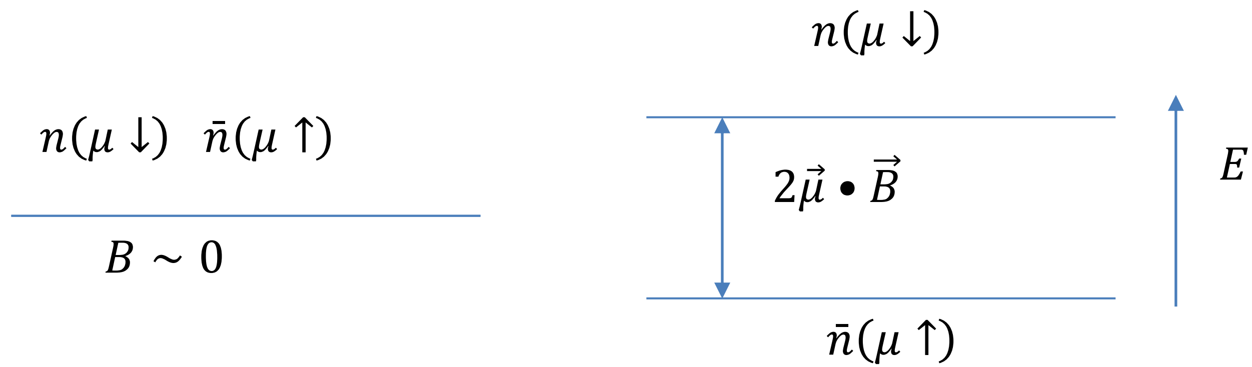


Eg double planar reflector



TPC + scintillators and lead-glass

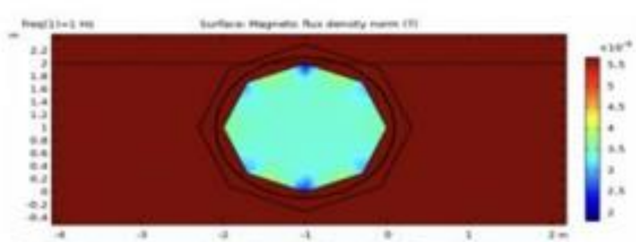
The need for magnetic shielding



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

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

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

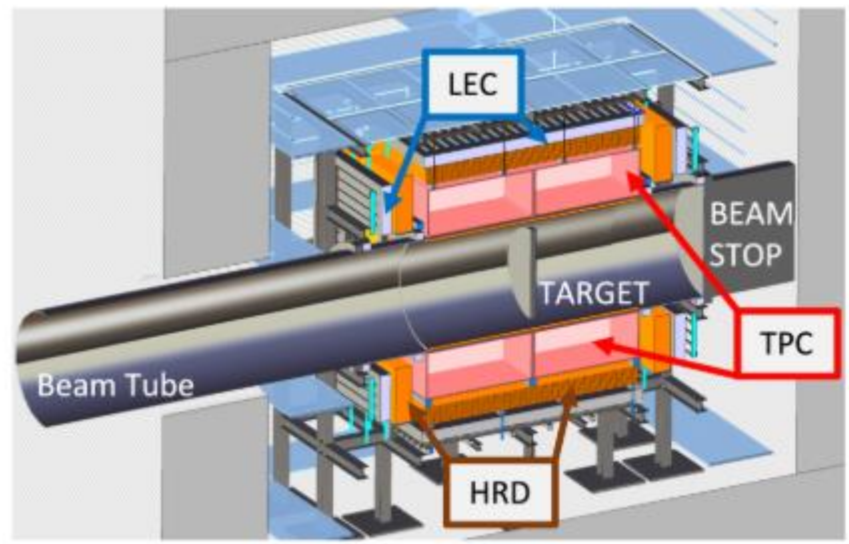


COMSOL

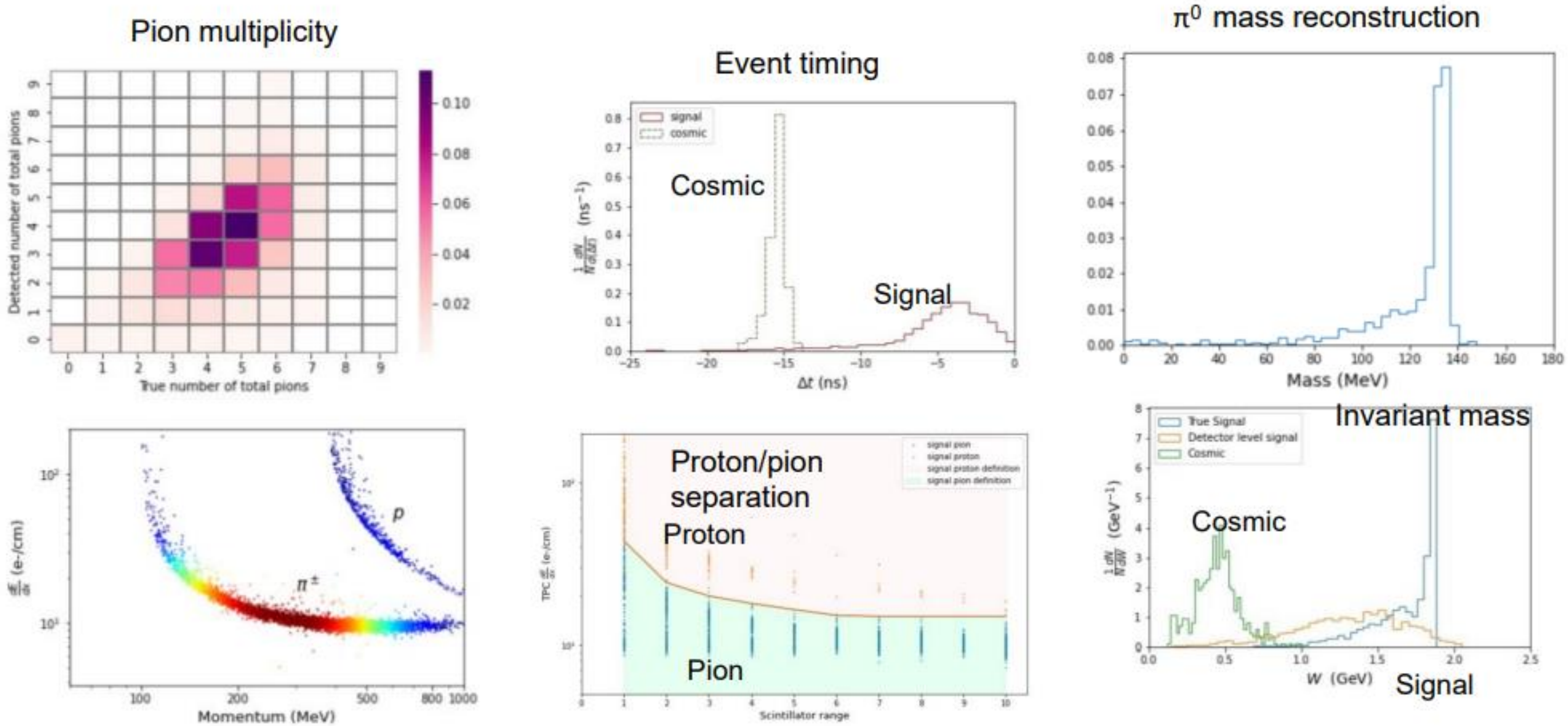
Residual B field <10 nT

NNBAR detector

- ~2 GeV invariant mass pionic final state
- Lead-glass em calo
- Scintillator staves
- TPC
- Cosmic veto (scintillators)



Geant-4 detector simulation



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, Bernhard Meirose, Joshua Barrow, Christian Bohm, Gustaaf Brooijmans, Katherine Dunne, Elena S. Golubeva, David Milstead, André Nepomuceno, Anders Oskarsson, Valentina Santoro and Samuel Silverstein

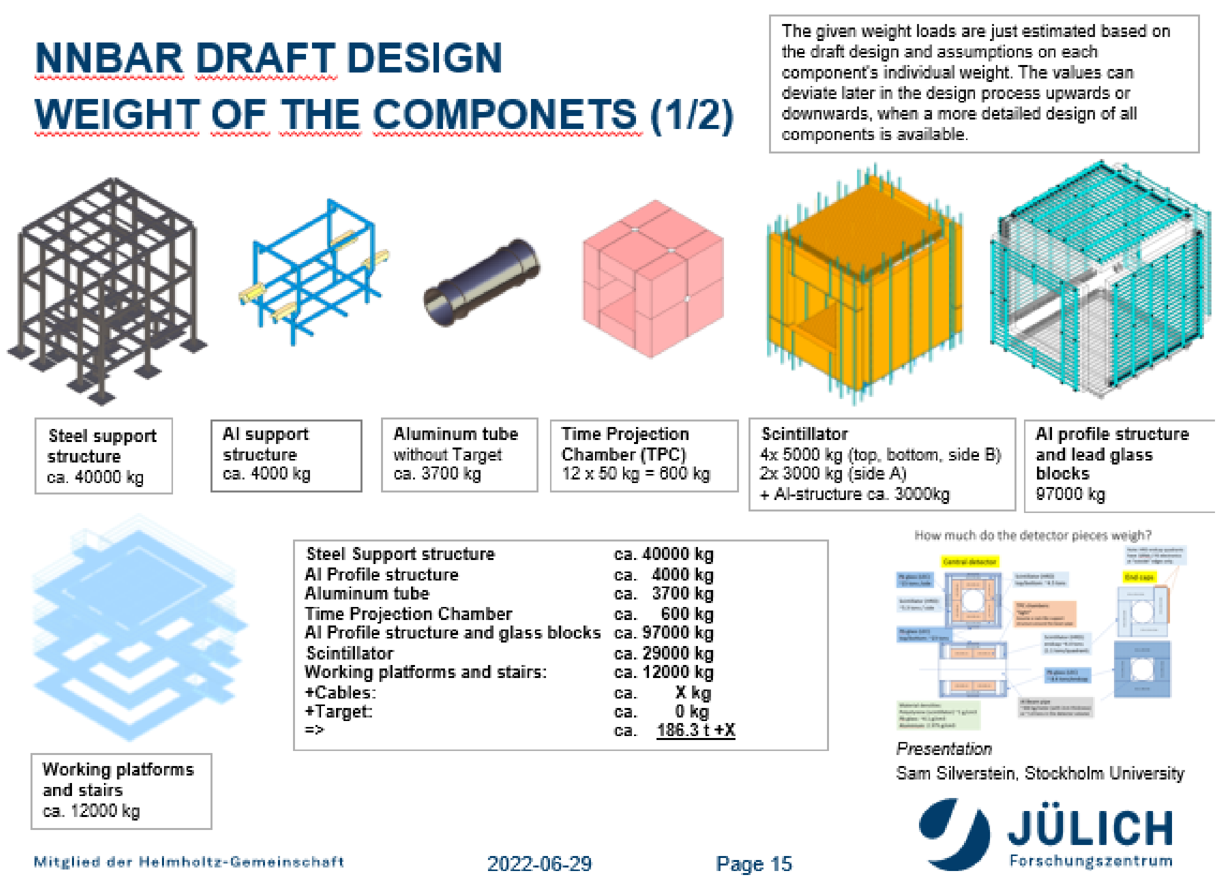
Symmetry 14 (2022) 1, 76

Backgrounds

- Cosmic rays (neutral and charged - dominant at ILL)
- Thermal neutrons, beta-delayed neutrons
- Low energy photons - from the activation of the target + beamline. While these are low energy (1 MeV), pile-up happens.
- Spallation bg -high energy, can be removed with timing
- Nuclear fragments
- Geant4 and MCNP study for different beamline configurations and neutron poisons

Mechanical assembly/design

Design study by Julich engineers/Sam S./Anders Oskarssson

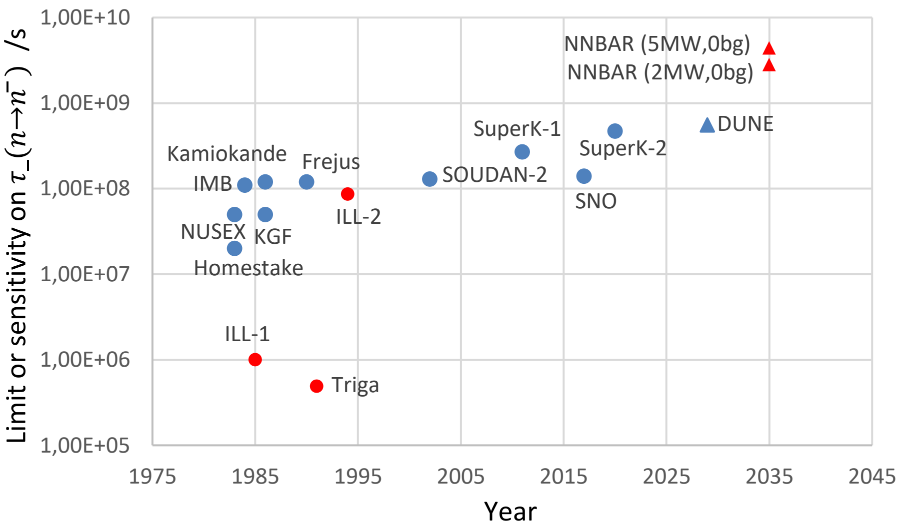


Capability of the experiment

Background suppression selections.

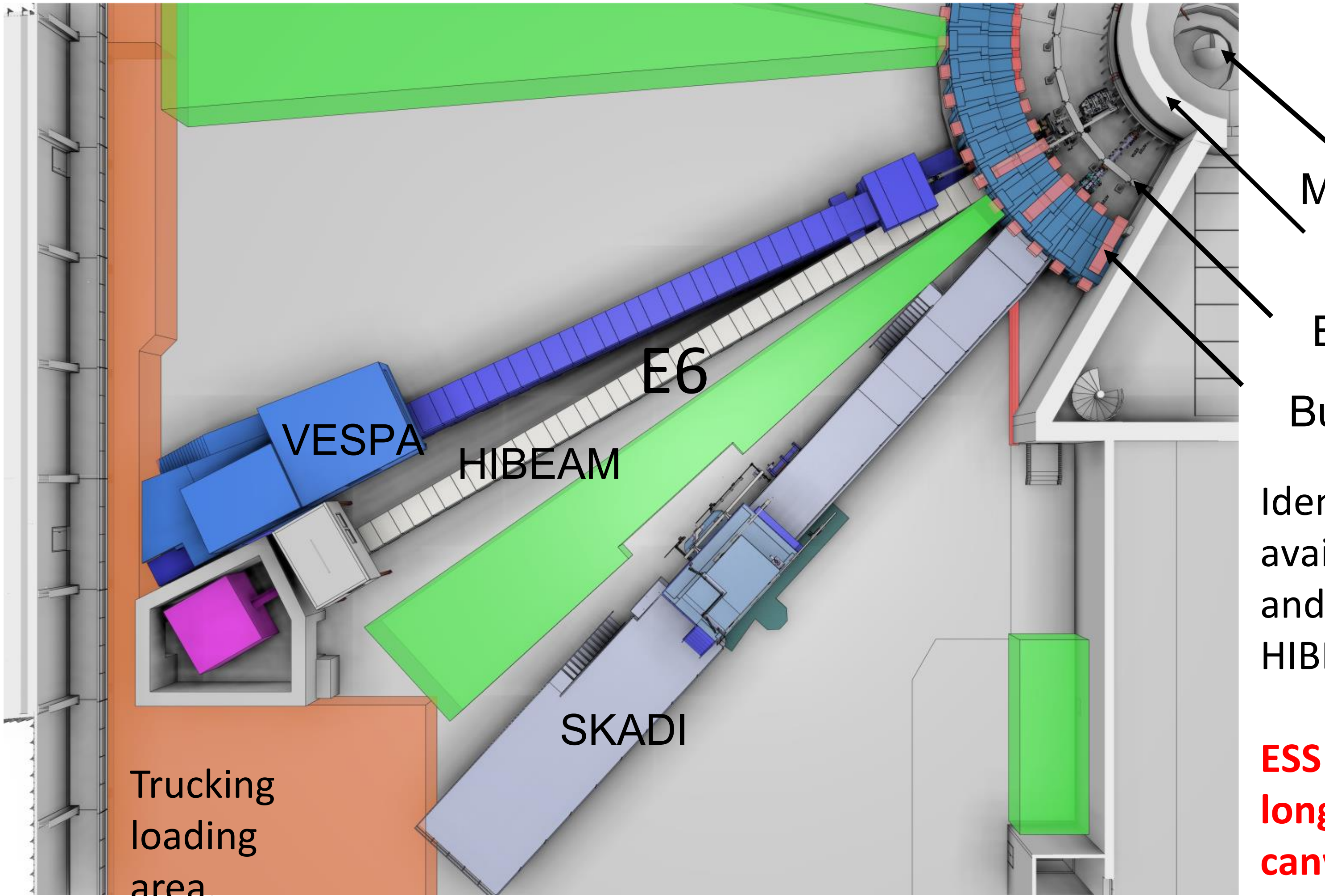
Selection	Signal	Non-muon background	Muon background
Scintillator energy loss $\in [20, 2000]$ MeV	0.89	0.008	0.3
TPC track cut	0.87	2.3×10^{-3}	9.0×10^{-3}
Pion count $\geqslant 1$	0.82	7.8×10^{-9}	5.9×10^{-4}
Invariant mass $W \geqslant 0.5\,\mathrm{GeV}$	0.8	7.8×10^{-9}	1.5×10^{-4}
Sphericity $\geqslant 0.2$	0.71	1.8×10^{-11}	7.8×10^{-9}
$E_{\mathrm{scint},\,y>0,\,\mathrm{filtered}} \leqslant 320\,\mathrm{MeV}$ & $E_{\mathrm{scint},\,y<0,\,\mathrm{filtered}} \leqslant 930\,\mathrm{MeV}$	0.68	-	-

10^3 increase in discovery potential compared to previous experiment



HIBEAM

HIBEAM optimal beamline: E6



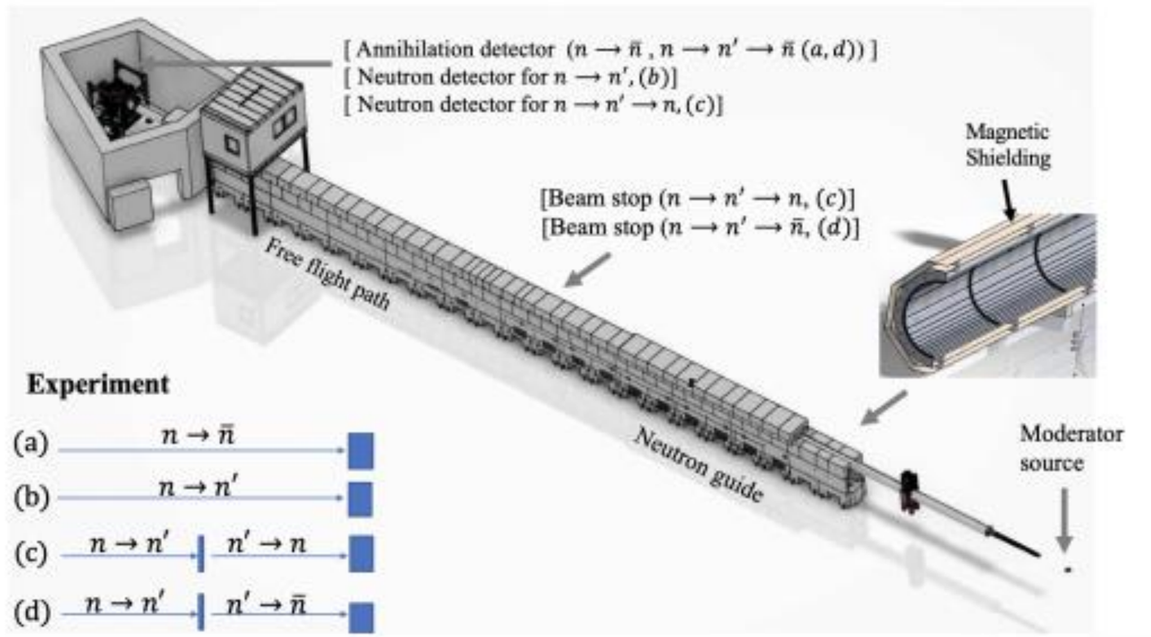
Identified available room and designed HIBEAM to fit.

ESS is no longer a 'blank canvas' for beamline design.

Investment by ESS for beam extraction system of HIBEAM design (1.1MEuro). Without this, impossible for any new instrument to operate before 2030's.

HIBEAM neutron conversions searches

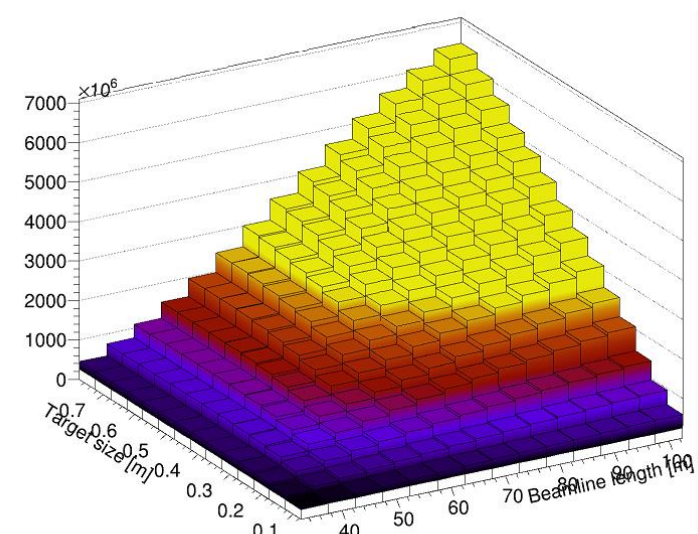
$$\hat{\mathcal{H}} = \begin{pmatrix} m_n + \vec{\mu}_n \vec{B} & \varepsilon_{n\bar{n}} & \alpha_{nn'} & \alpha_{n\bar{n}'} \\ \varepsilon_{n\bar{n}} & m_n - \vec{\mu}_n \vec{B} & \alpha_{n\bar{n}'} & \alpha_{nn'} \\ \alpha_{nn'} & \alpha_{n\bar{n}'} & m_{n'} + \vec{\mu}_{n'} \vec{B}' & \varepsilon_{n'\bar{n}'}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



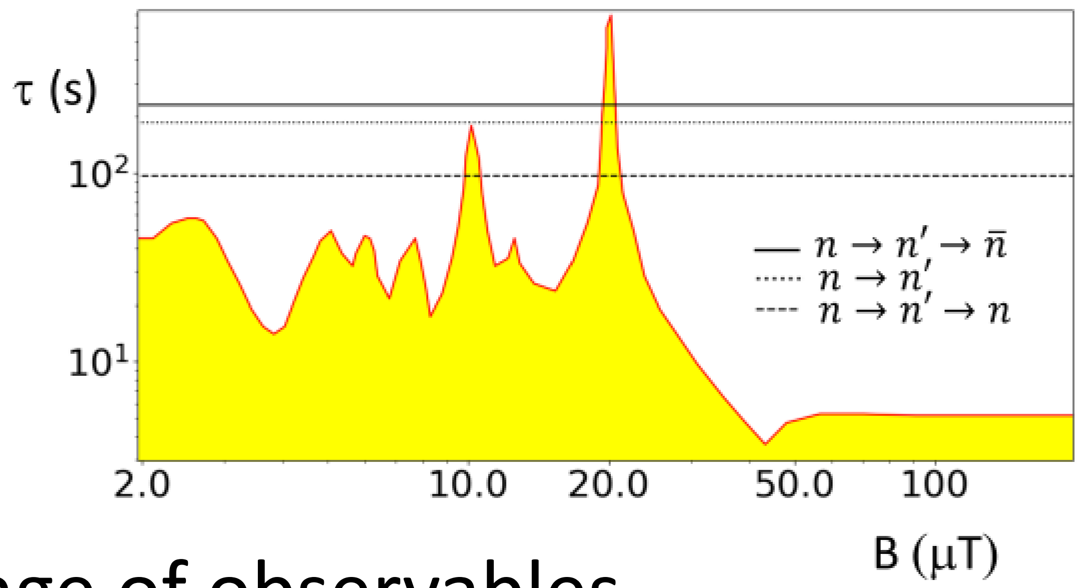
Sensitive to the full mixing Hamiltonian for $n, \bar{n}, n', \overline{n'}$

Can use bespoke annihilation detector or WASA (CsI) crystal calorimeter co-owned by UU.

Can exceed ILL experiment by factor 10



Sterile neutron searches



- Range of observables
- Order of magnitude improvement in sensitivity.

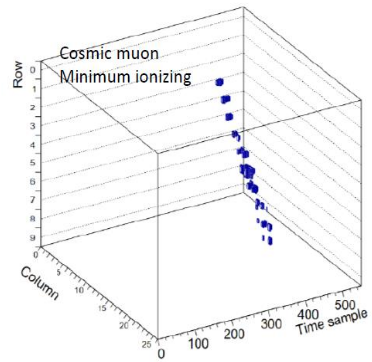
Getting to HIBEAM

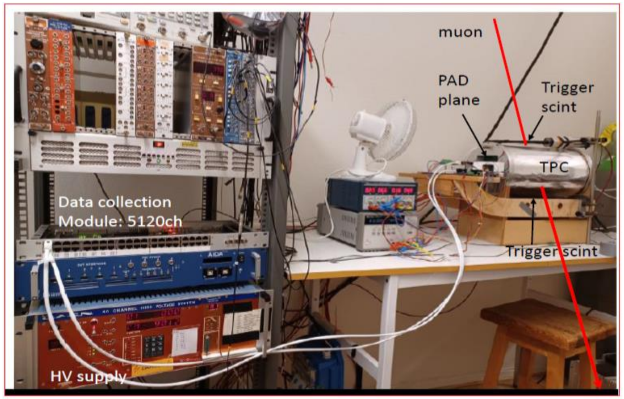
VR RFI

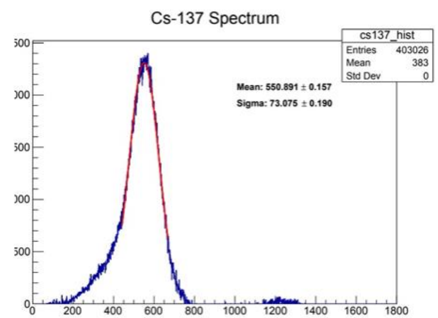
Stockholm, Lund, Chalmers, ESS

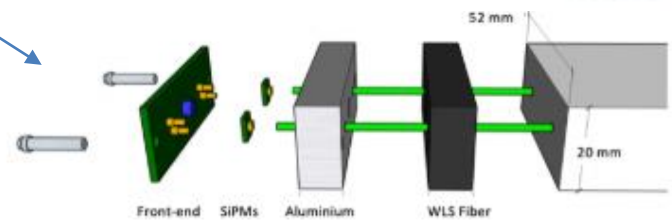
Prototype development
- TPC
- WASA crystal calorimeter
- Scintillator/lead-glass calorimeter

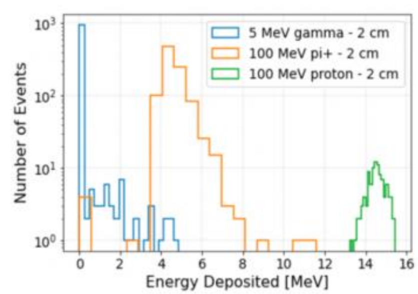
Annihilation detector
Neutron detector
Beamline design

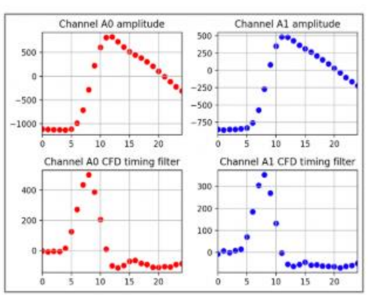












Axions@HIBEAM

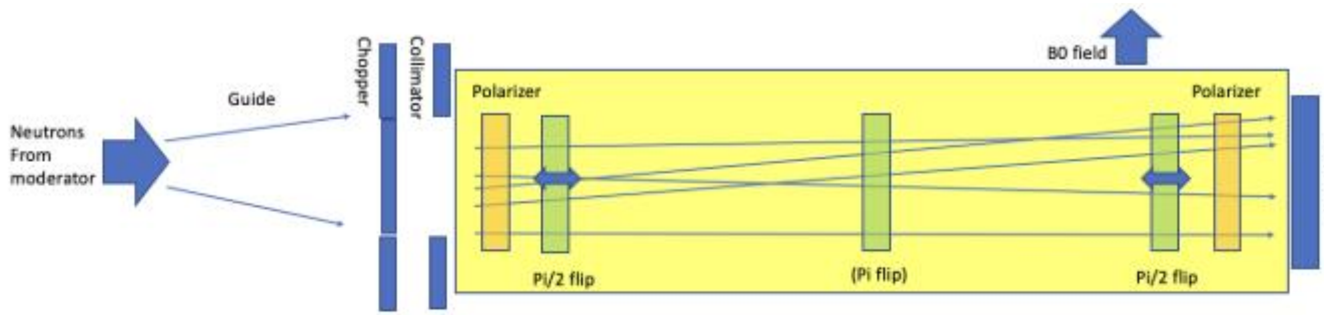
Dark matter candidate - axion.
Coupling of axions to a nucleon
Axions act as a pseudomagnetic field

$$H_{\text{int}}(t) \approx \frac{C_N a_0}{2 f_a} \sin(m_a t)\, \boldsymbol{\sigma}_N \cdot \boldsymbol{p}_a$$

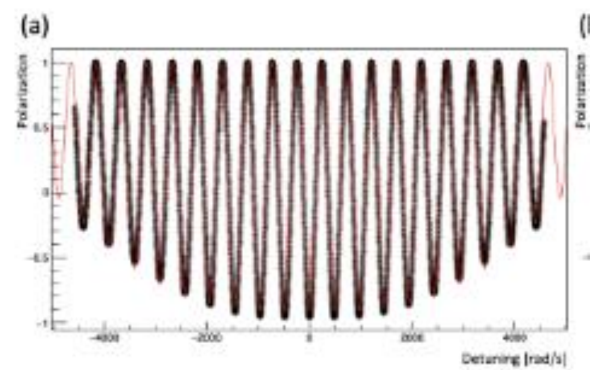
Change in Larmor frequency due to axions

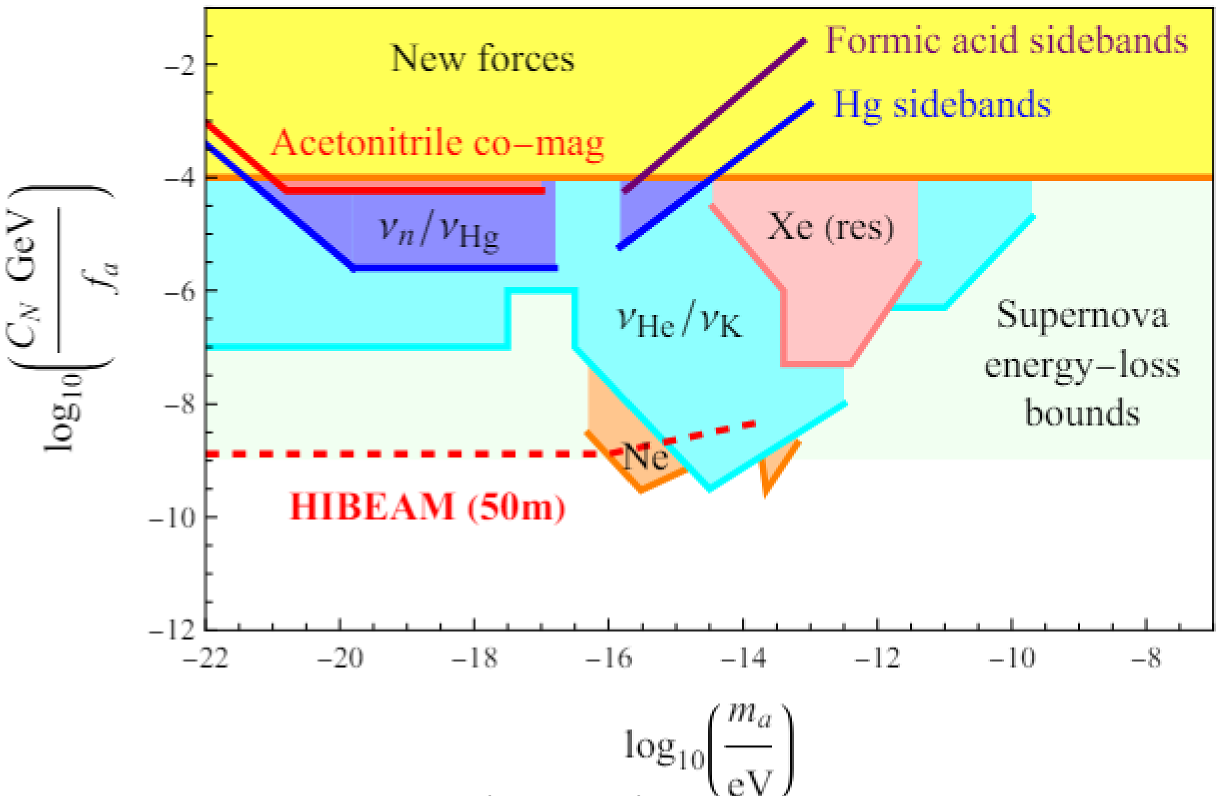
$$\hbar\omega_L = -\gamma \boldsymbol{\sigma}_N \boldsymbol{B} = H_{\text{int}}(t).$$

Ramsey set up for Lar



Fringe shifts





Arxiv:2404.15521 (hep-ph)

A small-scale pilot experiment at the ESS is funded.

Many uses for HIBEAM beyond neutron-antineutron – neutron charge, nEDM ….

HIBEAM/NNBAR

Started as an Expression of Interest for a neutron-antineutron search at the ESS (2015)

Signatories from 26 institutes, 8 countries.

Developed into multi-stage HIBEAM/NNBAR project

Co-spokespersons: G. Brooijmans (Columbia), D. Milstead (SU)
Lead scientist: Y. Kamyshkov (Tennesee)
Technical Coordinator (V. Santoro)
Prototype coordinator (M. Holl)

Many active institutes: SU,CTU,UU,LU (SV), TMU (DE), Tennessee, Columbia, ORNL (US), Krakow (PL), Brazil (Rio), Poland (Krakow)….

HIBEAM is supported by the Swedish Research Council (1.4MEuro (completed), 0.48Euro) , the Swedish Foundation for Research Strategy (1.5MEuros), Olle Engkvist Foundation (0.4MEuro)
+ VR grant for collaborating with Italian institutes

NNBAR was supported as part of a 3MEuro H2020 grant for an upgraded ESS with a new lower moderator.

STINT award for collaboration with Brazilian institutes (B. Meirose).

Synergy Grant (SU, LU, TMU, Indiana) for ~construction of HIBEAM and first nnbar, nn' searches.

Selection of HIBEAM/NNBAR publications

OPEN ACCESS
IOP Publishing
Journal of Physics G: Nuclear and Particle Physics
J. Phys. G: Nucl. Part. Phys. 48 (2021) 070501 (76pp)
https://doi.org/10.1088/1361-6471/abf429

Major Report

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

'White paper'

Journal of Neutron Research 25 (2023) 315–406
DOI 10.3233/JNR-230951
IOS Press

HighNESS conceptual design report: Volume II. The NNBAR experiment.

NNBAR CDR

EPJ Web of Conferences 251, 02062 (2021)
https://doi.org/10.1051/epjconf/202125102062
CHEP 2021

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

'Software framework'

International Conference on Technology and Instrumentation in P...
Journal of Physics: Conference Series 2374 (2022) 01...

The HIBEAM/NNBAR Calorim...

K Dunne[1], B Meirose[1,3], D Milstead[1], V Santoro[2], S Silverstein[1] and S-C Yiu
[1] Department of Physics, Stockholm University, 106 ...
[2] European Spallation Source ERIC, 225 92, Lund, S...
[3] Fysiska institutionen, Lunds universitet, 221 00, Lu...
E-mail: katherine.dunne@fysik.su.se

'Prototype construction'

[physics.ins-det] 14 Nov 2023

The HIBEAM program: search for neutron oscillations ... the ESS

HIBEAM monolith insert, optics and status

symmetry MDPI

Article

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

Sze-Chun Yiu, Bernhard Meirose, Joshua Barrow, Christian Bohm, ... Katherine Dunne, Elena S. Golubeva, David Milstead, André Nepo... Valentina Santoro and Samuel Silverstein

'Detector design'

Physics Reports 1023 (2023) 1–84
Contents lists available at ScienceDirect
Physics Reports
www.elsevier.com/locate/physrep

...Spallation Source

'ESS particle physics community review paper' (initiated and driven by DM/VS)

A Ramsey Neutron-Beam Experiment to Search for Ultralight Axion Dark Matter at the ESS

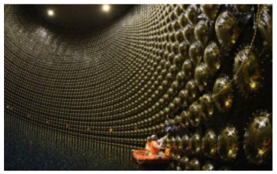
'Axions'

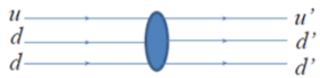
[hep-ph] 4 May 2024

1. INTRODUCTION

+ *JINST* 17 (2022) 10, P10046 (Arxiv: 2209.09011, [physics.ins-det])
+ Proc AccApp 21 (arXiv: 2204.04051 [physics.ins-det])
+ ....

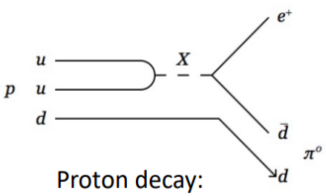
Fitting into the European landscape



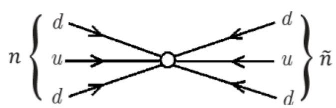


Neutron-sterile neutron:
$n \longrightarrow n', \Delta B = 1, \Delta L = 0$

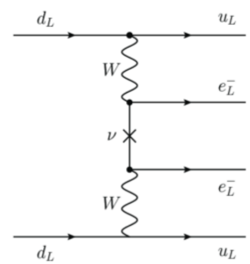
Relatively unexplored selection rules HIBEAM/NNBAR



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.***

Summary

- Neutron oscillations are a key but rarely explored portal for new physics
  - baryogenesis, BNV physics, dark matter
- The ESS is opening a new discovery window
- HIBEAM/NNBAR is a multi-stage program to increase sensitivty by ~1000
  - From prototype development to physics
- HIBEAM offers a wide range of applications (neutron oscillations, axions, rare decays etc.).
- Always on the look-out for new collaborators!!

Neutron-antineutron oscillations

- R-parity violating supersymmetry
- Extra dimensions
- Post-sphaleron baryogenesis
- Left-right symmetric models
- etc. etc.