The European Spallation Source and Future Free Neutron Oscillations Searches

Valentina Santoro
ESS
on behalf of the NNBAR Collaboration

Outline

- Scientific case
- Previous Searches
- The European Spallation Source
- The HIBEAM experiment (2023-2027)
- The NNBAR experiment > 2030

"Moses, this chapter outline is really impressive."

Baryon Number Violation

- *BN* is an "accidental" global symmetry at perturbative level
  - *BNV* in SM non-perturbatively (eg instantons)
  - *B-L* is conserved, not *B, L* separately.
- *BNV* needed for baryogenesis
- *BNV* generic features of SM extensions (eg SUSY, extra dimensions …)
- Very good reason to believe that *BNV* is a part of Nature
- Important to probe possible *BNV* channels
- HIBEAM/NNBAR : searches for $n \to \bar{n}$ $(|\Delta B| = 2)$ and $n \to n'(|\Delta B| = 1)$.
- **Sensitivity increase of 10^3 compared with previous experiments.**

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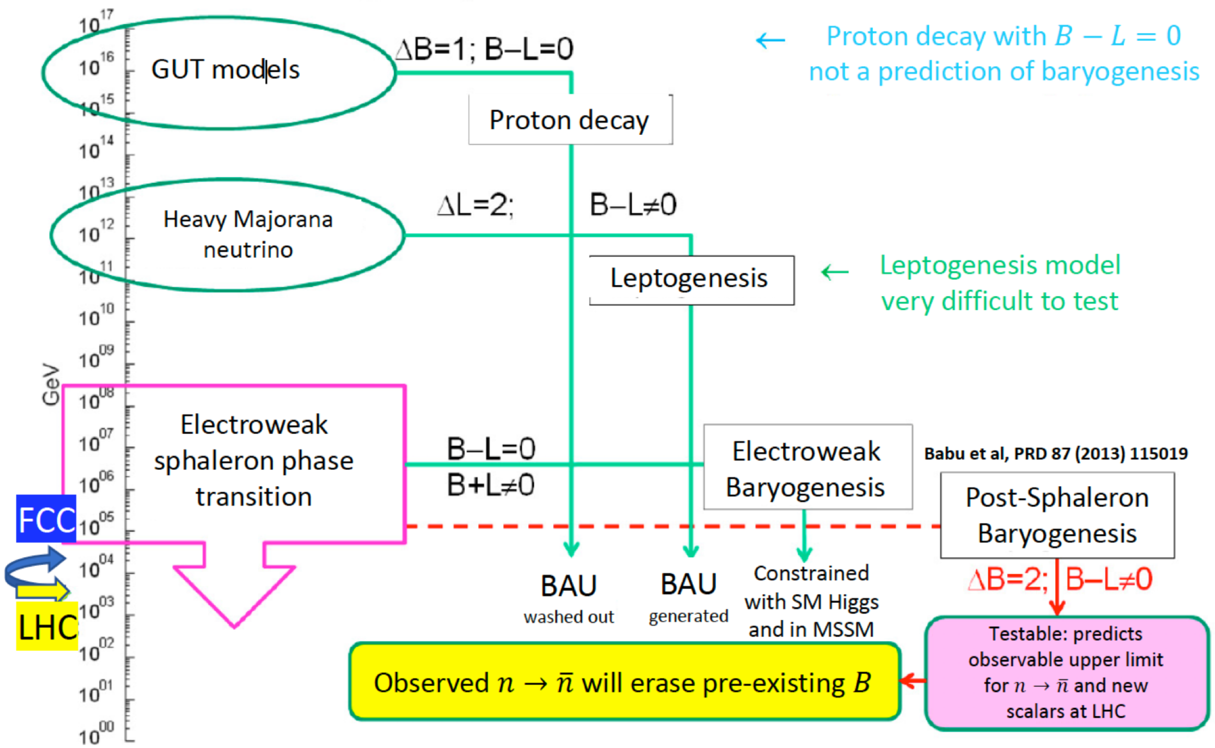
Baryogenesis Models

Regimes for baryogenesis

- Leptogenesis: Sphalerons convert L into B
- Electroweak baryogenesis: T violation near EW scale creates B without L
- Post-sphaleron baryogenesis: New BNV process below EW phase transition
- $n \to \bar{n}$ targets accessible energy scales . Null result will restrict phase space of PSB models

see talk Rabi Mohapatra



Phenomenology of neutron conversion processes

$$\boldsymbol{\Psi} = \binom{n}{\bar{n}'}$$

Mixed $n, \bar{n}, n'$ QM state

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

ε is the mixing mass term that depends on the scale of the new physics

the mass mixing term ε is different for $n \to \bar{n}$ and $n \to n'$

$m_n = m_{\bar{n}}$ by CPT invariance, E_n and $E_{\bar{n}}$ are **not** generically equal due to enviromental effects (i.e. matter medium or magnetic fields)

Probability to find an antineutron at time t is given by

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

$\Delta E = E_n - E_{\bar{n}}$ and τ_n (mean life time of the free neutron)

-> the probability of conversion is suppressed when the energy degeneracy between neutron and antineutron is broken.

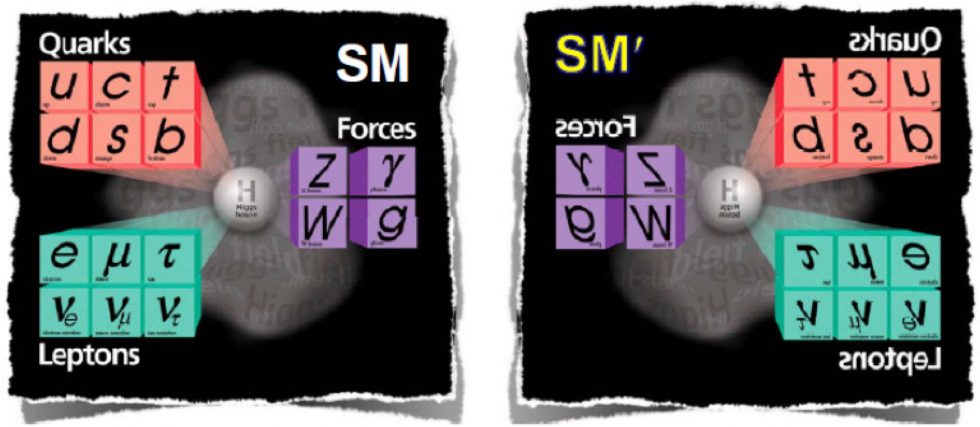
Quasi free regime $|\Delta E|t \ll 1$ can be realized in vacuum with very low magnetic shield. Under this condition

$$P_{n\to\bar{n}}(t) = \left(\frac{t_{free}}{\tau_{n\to\bar{n}}}\right)^2$$

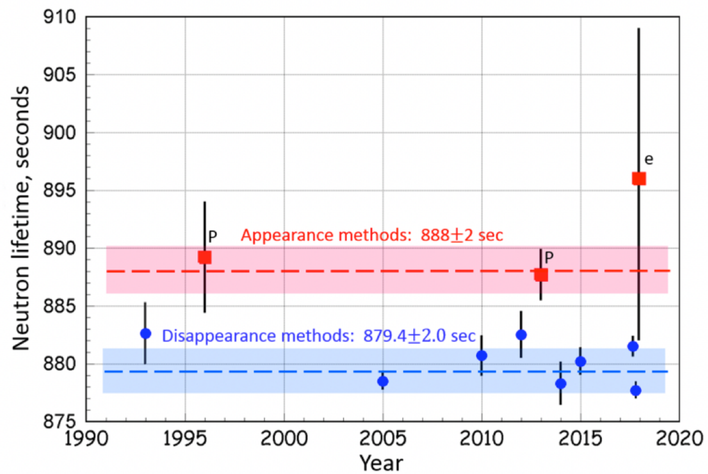
Figure of merit (background-free): Nt^2

Mirror Neutrons

- As a meta-stable neutral particle, the neutron is one of the few possible portals to a hidden/dark sector. (e.g. mirror matter and generic dark sectors)
- These transitions can also shed light on the anomaly between neutron lifetime in "beam" and "bottle"
- These searches part of the experimental program at the European Spallation Source



- Z. Berezhiani, Phys. Rev. Lett. 96 (2006) 081801
- Z. Berezhiani, arXiv:hep-ph/0508233 (2005)
- R. Foot, Int. J. Mod. Phys. A29 (2014) 1430013
- Z. Berezhiani, Int. J. Mod. Phys. A29 (2014) 3775-3806



see Yury Kamyshov talk on Wednesday

F. E. Wietfeldt, "Measurement of Neutron Lifetime," Atoms 6(4) (2018)

Previous and Current Searches

Search for neutron antineutron oscillation in bound nuclei

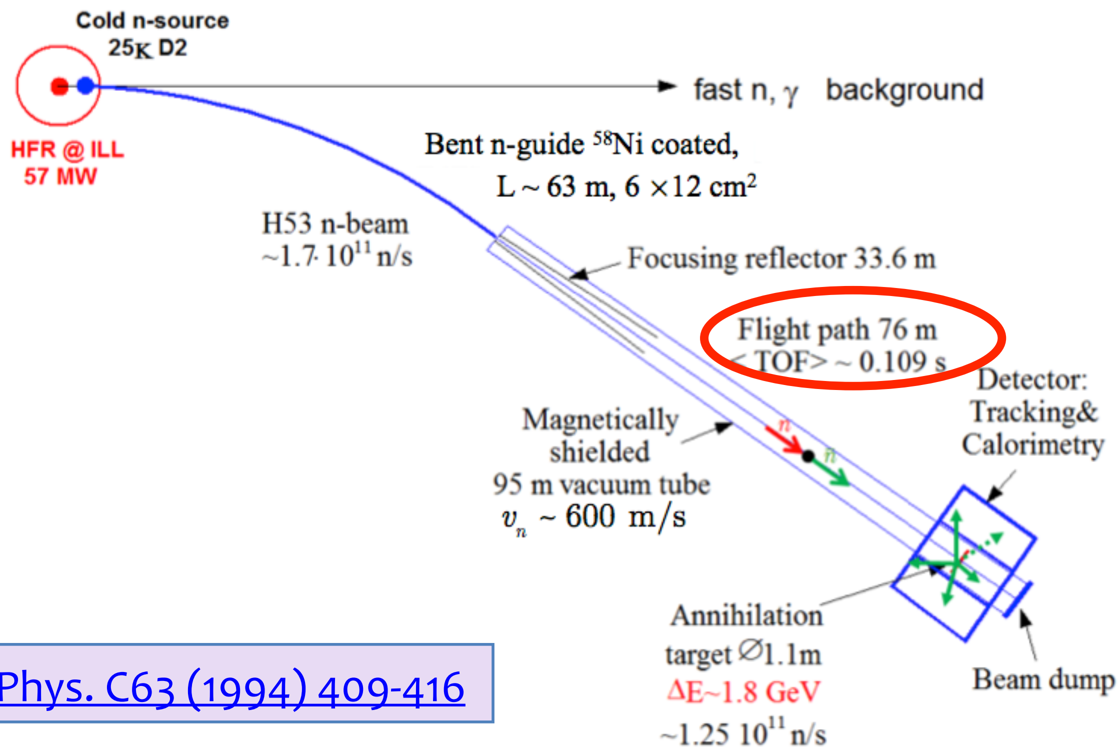
- For bound neutrons in a nucleus, the potential energy difference experienced between a neutron and antineutron in the strong nuclear field (ΔE is ~ 10-100 MeV) , introduces a suppression of 10^{31} with respect to the conversion of a free neutron.
- Sensitive searches only possible with large volume detectors such as Super-Kamiokande, SNO, DUNE ecc.
- The comparatively large number of neutrons permits searches with currently complementary limits.
- Best current limit is coming from Super-Kamiokande (searches are background limited)

$$\tau_{n\bar{n}} > 2.7 \times 10^{8}\ \text{s, or equivalently}\ \varepsilon_{n\bar{n}} < 2.5 \times 10^{-24}\ \text{eV.}$$

see Linyan Wan and Josh Barrow talk

K. Abe *et al.*, Phys. Rev. D91 (2015) 072006

Search for neutron antineutron oscillation @ ILL



Baldo-Ceolin et al, Z.Phys. C63 (1994) 409-416

$Nt^2 = 1.5\ 10^9$s, $P < 1.6\ 10^{-18}$ (run lasted ~1 year) and $\tau_{n \to \bar{n}} > 0.86\ 10^8$s
(***N*** is the free neutron flux reaching the annihilation target and ***t*** is the neutron observation time).

Many subtle optimizations to minimize losses and backgrounds

Experiment was background-free

The European Spallation Source

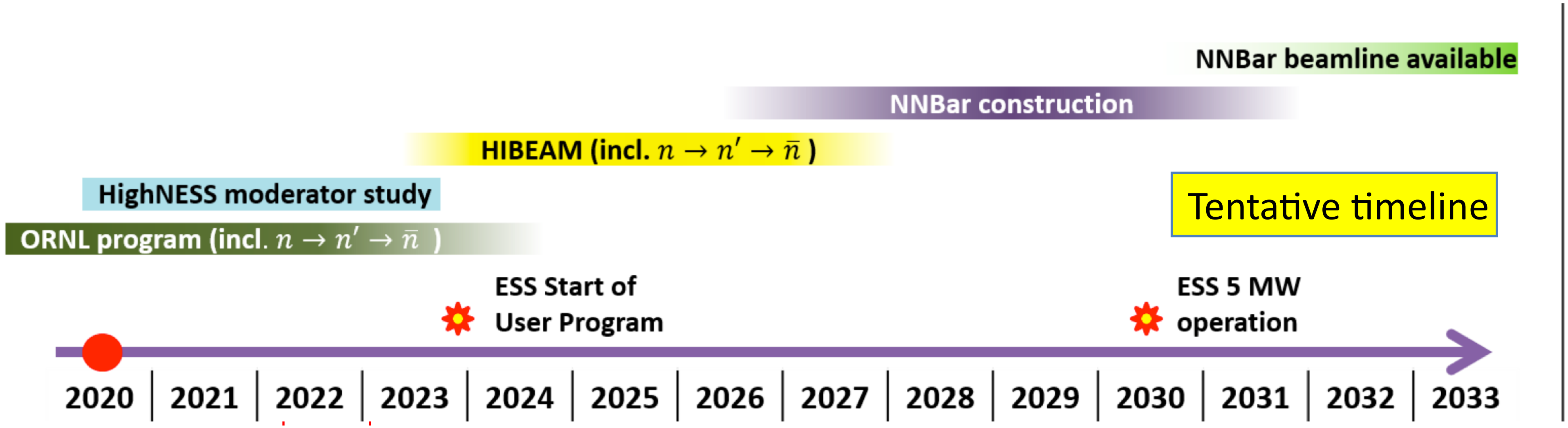
- The European Spallation Source is under construction in Lund, a city in southern Sweden.
- The facility's unique capabilities will both greatly exceed and complement those of today's leading neutron sources, enabling new opportunities for researchers across the spectrum of scientific discovery, including materials and life sciences, energy, environmental technology, cultural heritage and fundamental physics.

ESS Timeline	GROUNDBREAKING	INITIAL OPERATIONS	INSTRUMENT COMMISSIONING BEGINS	USER PROGRAMME BEGINS	PROJECT COMPLETION STATUS
	2014	2019	2022	2023	70%

The NNBAR experiment at ESS

- ESS intended for n-scattering experiment , but significant component will be fundamental physics research including **n-nbar search**
- NNBAR Collaboration: search for nnbar using the "Large Beam Port" already constructed by ESS with NNBAR in mind
- LD2 cold moderator studies underway ($3MEURO funded by the European Commission ``HighNESS project``)
- NNBAR Beamline earliest available ≥ 2030
- HIBEAM: smaller program of complementary experiments (with focus on mirror neutron searches) ≳2023
- Collaborating with ORNL program on earlier time-scale (now underway)

see Marcel Demarteau talk on Wednesday



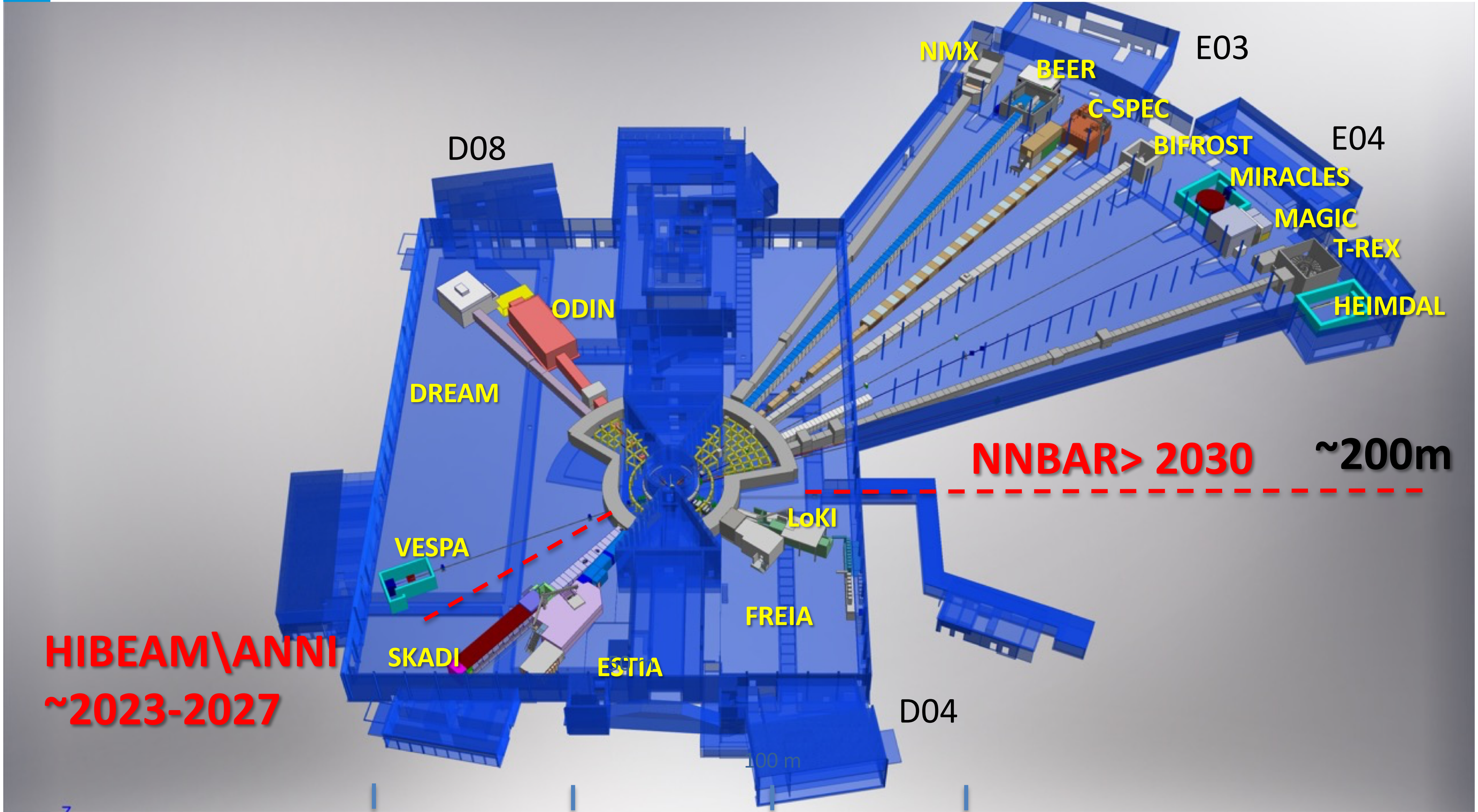
Sensitivity of the NNBAR experiment at ESS

- **Increase number of neutrons**
  - Flux
  - Moderator brightness and area
  - Angular acceptance
  - Longer run
- **Increase time-of-flight**
  - Longer beamline
- Keep (or even increase) detection efficiency (~50%), keep background at ~0
- **Better B_{Earth} suppression**

Factor	Gain wrt ILL
Source Intensity	≥ 2
Neutron Reflector	40
Length ($\propto t^2$)	5
Run time	3
Total gain	≥ 1000

NNBAR final design aim to improve by 10^3 the ILL limit

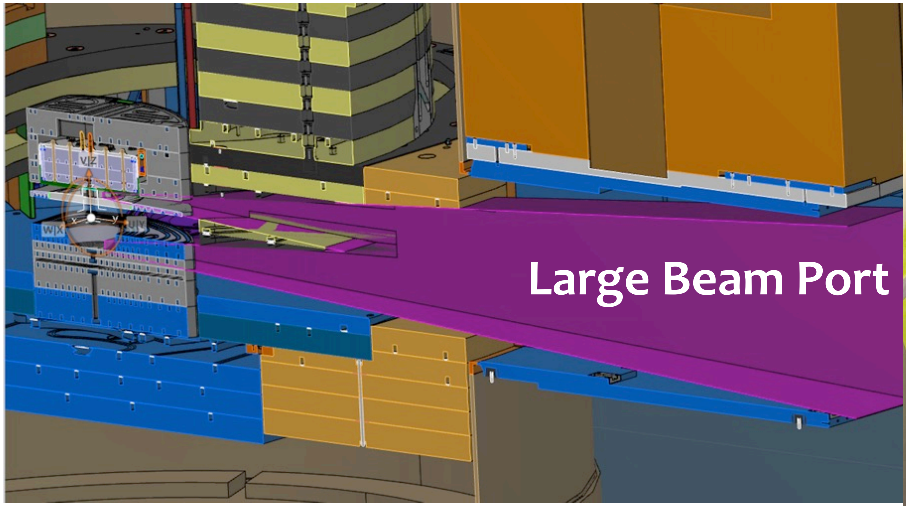
ESS Neutron Instruments 1-15 and HIBEAM and NNBAR locations



The Large Beam Port

- LBP has been constructed and will provide sufficient intensity for $n \rightarrow \bar{n}$ search
- Room for 200m of large diameter neutron beamguide

NNBAR collaborator in the ESS LINAC



"The Large Beam Port is an opportunity to broaden the ESS mission"
Rikard Linander Head of the ESS Target Division

Clock-non reset possibility

- Baseline assumes free flight time since last bounce
  Bounce stops oscillation clock… or does it?

- With appropriate choice of material potential, n and $\bar{n}$ wavepackets can continue to propagate coherently

- Implications very exciting—allowing few bounces reduces required diameter, complexity and cost of experiment

- Needs demonstration for confidence in idea (spin-echo with Gd material)

- Needs better understanding of antineutron scattering length (investigate with antiprotons)

- Important to study: **but not currently the baseline**

see W. Mike Snow talk

- V.V. Nesvizhevsky, V. Gudkov, K.V. Protasov, W. M. Snow, and A.Yu. Voronin, ``A new operating mode in experiments searching for free neutron-antineutron oscillations based on coherent neutron and antineutron mirror reflection``**,** Phys. Rev. Lett. **122**, 221802 (2019).
- V. Gudkov, V.V. Nesvizhevsky, K.V. Protasov, W.M. Snow, and A.Yu. Voronin, ``A new approach to search for free neutron-antineutron oscillations in coherent neutron propagation in gas`` , Phys. Lett. B**808**, 135636 (2020).

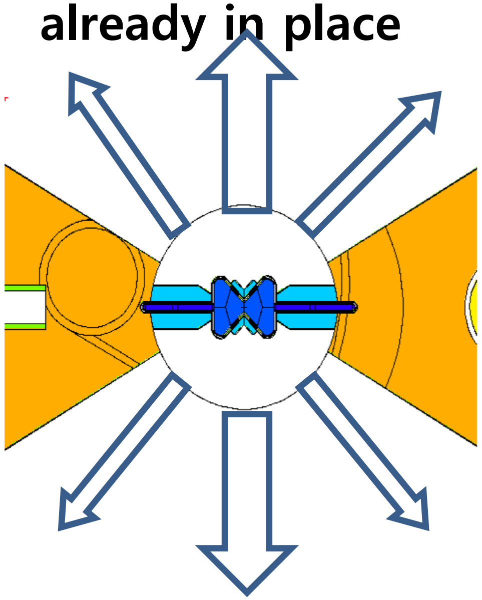
The HighNESS project at ESS

The HighNESS project ($3MEURO funded by the European Commission) has as purpose the development of the new source that will be installed at ESS >2030

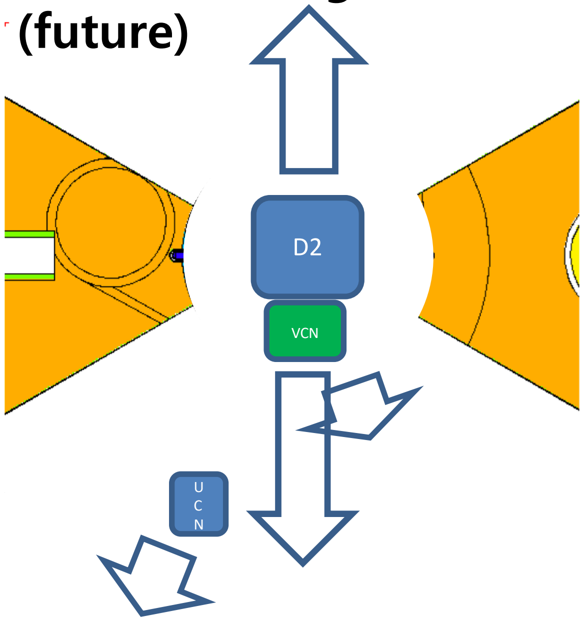
The new source will be composed by Liquid deuterium moderator that will serve a UCN moderator and a VCN moderator.

In the project will be also developed the NNBAR experiment **-> Conceptual Design Report expected by the end of 2023**

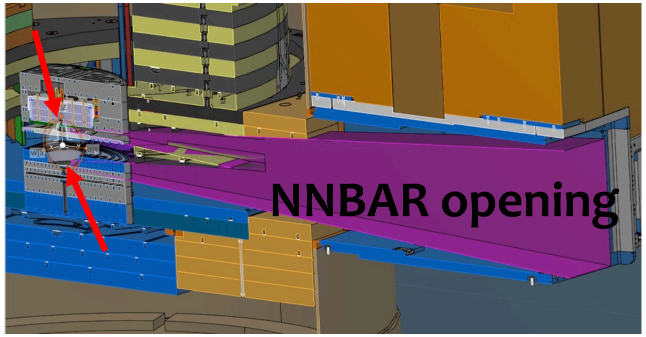
ESS current moderator. Located above the target already in place



ESS Liquid Deuterium moderato. Located below the target (future)



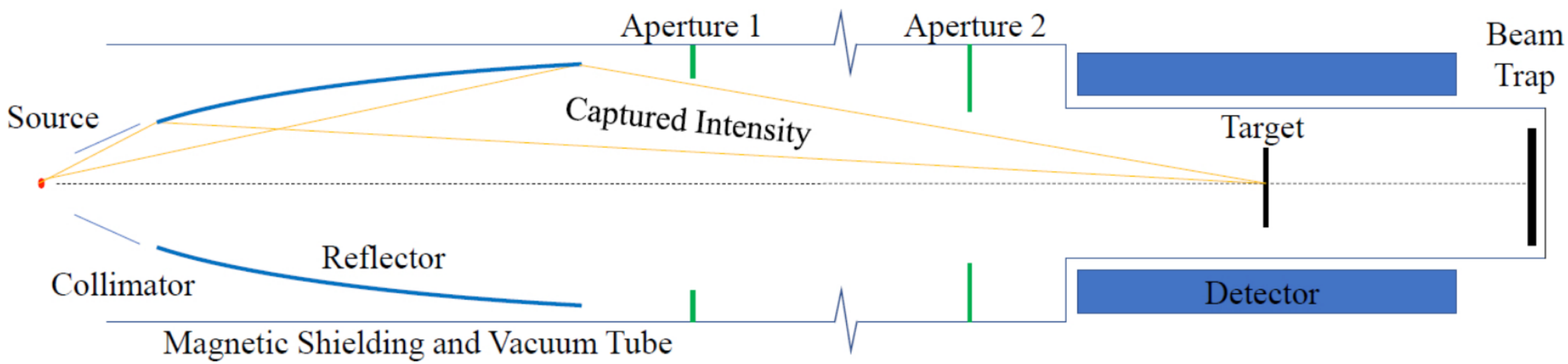
ESS current moderator



ESS Liquid Deuterium moderator

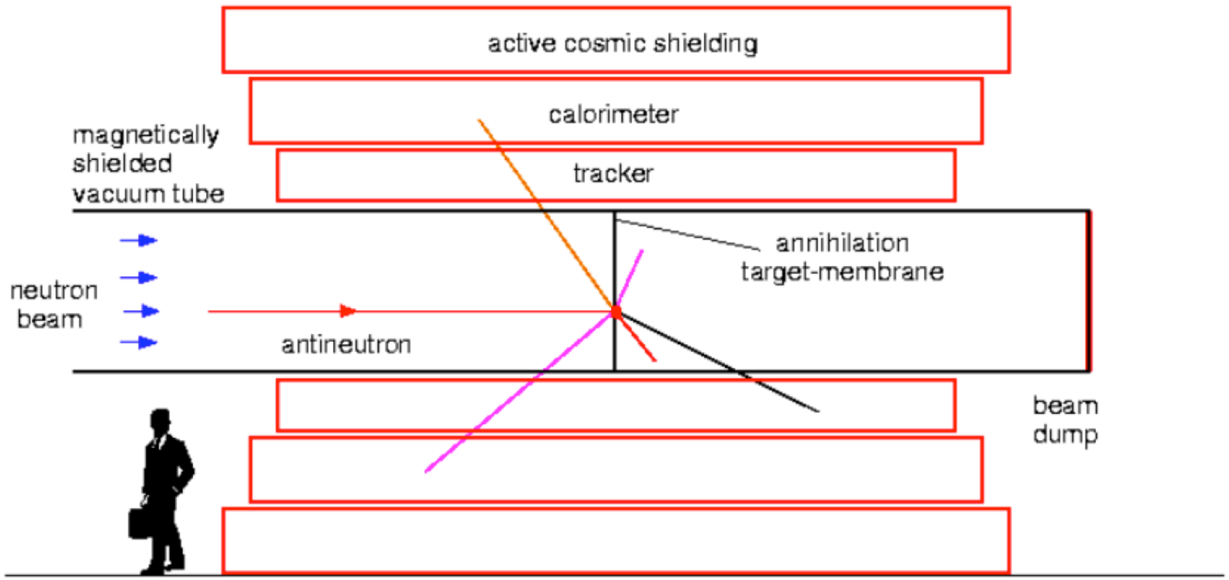
The liquid deuterium moderator will be designed in order to be optimal for NNBAR

The NNBAR experiment (schematic)



- High-m elliptical/balistic "super-mirror" reflector (PhD. Thesis Matt Frost) Free flight time in FOM is time since the last bounce
- Residual B field <5 nT
- Residual vacuum < 10^{-5} P
- NNBAR detector should be background free as in ILL experiment

The NNBAR detector

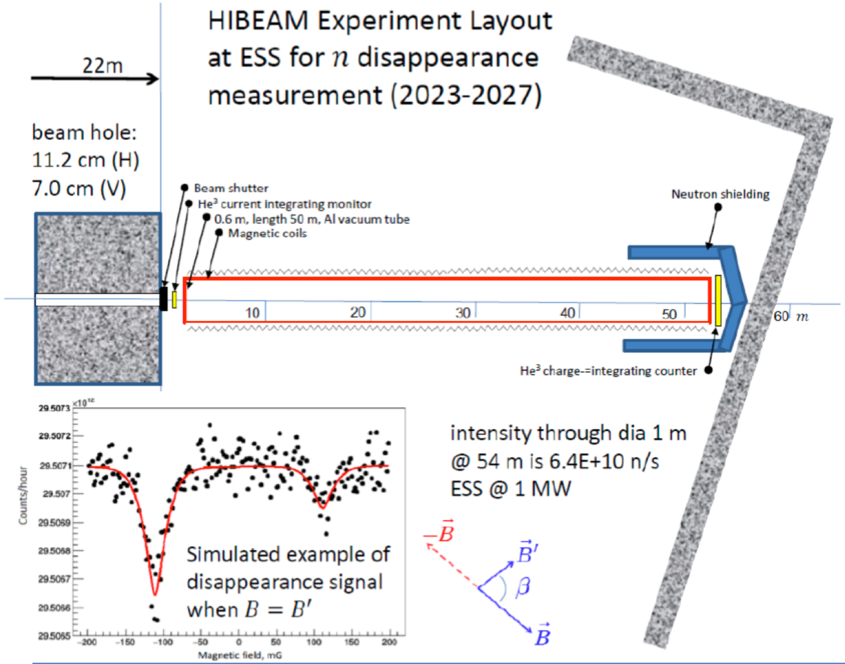


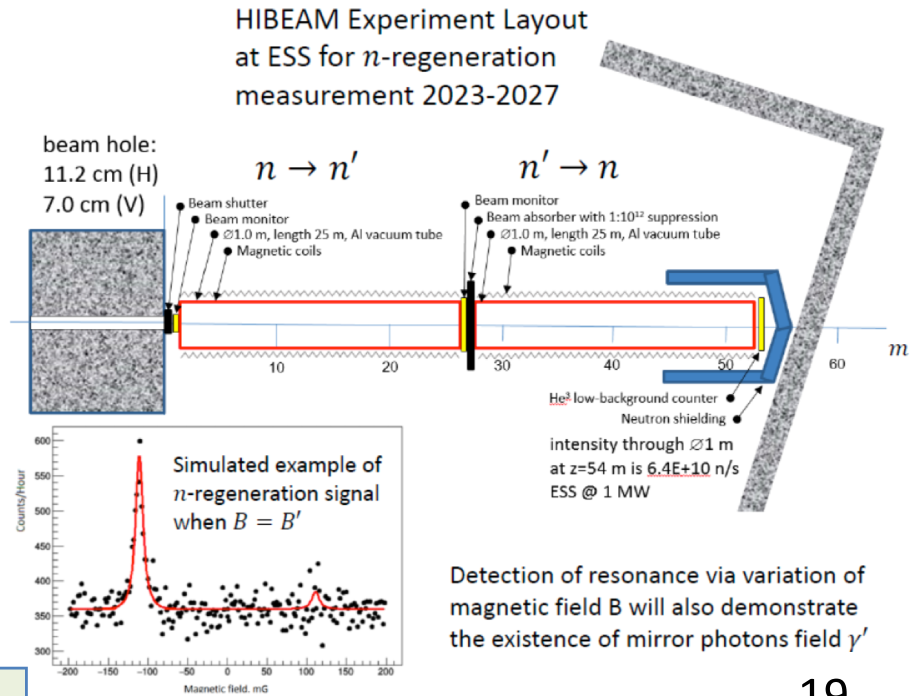
The neutron beam will hit a thin carbon foil target
The carbon has large $\bar{n}$ annihilation cross section , mostly transparent to neutrons
$\bar{n}N \rightarrow$ <5> pions (1.8 GeV)

Background suppression based on ILL experience
•precise vertex ID
•good resolution
•beam structure
•Important to perform background measurement: with magnetic field on/off or multiple targets

THE HIBEAM program 2023~2027

- A fundamental physics beamline is not a part of the first 15 instruments at ESS. ESS in his mandate has planned for 22 instruments.
- **High Priority for the next round of instrument will be given to the fundamental physics community**
- Two experimental collaborations: the ANNI beamline (A pulsed cold neutron beam facility for particle physics at the ESS) and the HIBEAM (High-Intensity Baryon Extraction and Measurement collaboration) have joined their effort for the fundamental physics beamline at ESS
- HIBEAM will look for n disappearance and n regeneration experiment





Detection of resonance via variation of magnetic field B will also demonstrate the existence of mirror photons field γ'

see Yury Kamyshov talk on Wednesday

Greatly Improve sensitivity over ORNL with optimized beamline

Conclusions

Lot of activities are going on right now:

- Earliest stages at ORNL:

  searches for $n \to n'$, $n \to n' \to \bar{n}$ oscillations
- HighNESS project will start in October:
  - Design of the optimal moderator configuration for NNBAR.
  - CDR of the NNBAR experiment. Detector development and design optimization. Simulations of backgrounds and shielding. Address uncertainties in cost of experiment

HIBEAM@ANNI ~ 2025: searches for sterile neutrons

NNBAR> 2030: x1000 improvement $\boldsymbol{n \to \bar{n}}$ @ILL

Improve by 10^3

- Baryon Number Violation at the core of our existence

Physics of Baryon Number Violation of utmost importance

- Standard Model tells us about interactions

But *nothing* about nature of quarks and leptons

Our existence, Grand Unification our best hints

- Baryon Number Violation excellent probe

We *know* it exists

- **Opportunities to gain a factor 1000 in sensitivity to processes at core of our existence and understanding of universe are rare**

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

arXiv:2006.04907

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

A. Addazi, K. Anderson, S. Ansell, K. Babu, J. Barrow, D.V. Baxter, P.M. Bentley, Z. Berezhiani, R. Bevilacqua, C. Bohm, G. Brooijmans, J. Broussard, R. Biondi, B. Dev, C. Crawford, A. Dolgov, K. Dunne, P. Fierlinger, M.R. Fitzsimmons, A. Fomin, M. Frost, S. Gardner, A. Galindo-Uribarri, E. Golubeva, S. Girmohanta, G.L. Greene, T. Greenshaw, V. Gudkov, R. Hall-Wilton, L. Heilbronn, J. Herrero-Garcia, G. Ichikawa T.M. Ito, E. Iverson, T. Johansson, L. Joensson, Y-J. Jwa, Y. Kamyshkov, K. Kanaki, E. Kearns, M. Kitaguchi, T. Kittelmann, E. Klinkby, L.W. Koerner, B. Kopeliovich, A. Kozela, V. Kudryatsev, A. Kupsc, Y. Lee, M. Lindroos, J. Makkinje, J.I. Marquez, R. Mohapatra, B. Meirose, T.M. Miller, D. Milstead, T. Morishima, G. Muhrer, H.P. Mumm, K. Nagamoto, V.V. Nesvizhevsky, T. Nilsson, A. Oskarsson, E. Paryev, R.W. Pattie Jr, S. Penttil, Y. N. Pokotilovski, I. Potashnikova, C. Redding, J-M Richard, D. Ries, E. Rinaldi, A. Ruggles, B. Rybolt, V. Santoro, U. Sarkar, A. Saunders, G. Senjanovic, A.P. Serebrov, H.M. Shimizu, R. Shrock, S. Silverstein, D. Silvermyr, W.M. Snow, A. Takibayev, L. Townsend, I. Tkachev, L. Varriano, A. Vainshtein, J. de VRies, R. Woracek, Y. Yamagata, A.R. Young, L. Zanini, Z. Zhang, O. Zimmer

The violation of Baryon Number, $\mathcal{B}$, is an essential ingredient for the preferential creation of matter over antimatter needed to account for the observed baryon asymmetry in the universe. However, such a process has yet to be experimentally observed. The HIBEAM/NNBAR %experiment program is a proposed two-stage experiment at the European Spallation Source (ESS) to search for baryon number violation. The program will include high-sensitivity searches for processes that violate baryon number by one or two units: free neutron-antineutron oscillation ($n \to \bar{n}$) via mixing, neutron-antineutron oscillation via regeneration from a sterile neutron state ($n \to [n', \bar{n}'] \to \bar{n}$), and neutron disappearance ($n \to n'$); the effective $\Delta\mathcal{B} = 0$ process of neutron regeneration ($n \to [n', \bar{n}'] \to n$) is also possible. The program can be used to discover and characterise mixing in the neutron, antineutron, and sterile neutron sectors. The experiment addresses topical open questions such as the origins of baryogenesis, the nature of dark matter, and is sensitive to scales of new physics substantially in excess of those available at colliders. A goal of the program is to open a discovery window to neutron conversion probabilities (sensitivities) by up to three orders of magnitude compared with previous searches. The opportunity to make such a leap in sensitivity tests should not be squandered. The experiment pulls together a diverse international team of physicists from the particle (collider and low energy) and nuclear physics communities, while also including specialists in neutronics and magnetics

BACK-UP SLIDES

Phenomenology of neutron conversion processes (II)

Probabilty to find an antineutron at time t is given by $P_{n\bar{n}}(t) = |\psi_{\bar{n}}(t)|^2$,

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

Where $\Delta E = E_n - E_{\bar{n}}$ and τ_n is the mean life time of the free neutron
-> the probability of conversion is suppressed when the energy degeneracy between neutron and antineutron is broken

In particular for free neutrons suppression occurs due to interaction of the magnetic field (B ~0.5G at the Earth)
To prevent significant suppression of the $n \rightarrow \bar{n}$ conversion we must keep the quasi-free regime $|\Delta E| t \ll 1$ that can be realized in vacuum with very low magnetic shield. Under this condition

$$P_{n\rightarrow\bar{n}}(t) = \left(\frac{t_{free}}{\tau_{n\rightarrow\bar{n}}}\right)^2$$

Figure of merit (background-free): Nt^2

Neutron-Antineutron transition probability

For $H = \begin{pmatrix} m_n + V & \alpha \\ \alpha & m_{\bar{n}} - V \end{pmatrix}$ $\quad P_{n\to\bar{n}}(t) = \dfrac{\alpha^2}{\alpha^2 + V^2} \times \sin^2\left[\dfrac{\sqrt{\alpha^2 + V^2}}{\hbar} t\right]$

where V is the potential difference for neutron and anti-neutron

For $\left[\dfrac{\sqrt{\alpha^2 + V^2}}{\hbar} t\right] << 1$ ("quasifree condition") $\quad P_{n\to\bar{n}} = \left(\dfrac{\alpha}{\hbar} \times t\right)^2 = \left(\dfrac{t}{\tau_{n\bar{n}}}\right)^2$

$\tau_{n\bar{n}} = \dfrac{\hbar}{\alpha}$ is characteristic oscillation time. Present limit -> $\alpha < 10^{-23} eV$!