

The HIBEAM Experiment at the ESS

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Baryon and lepton number violation

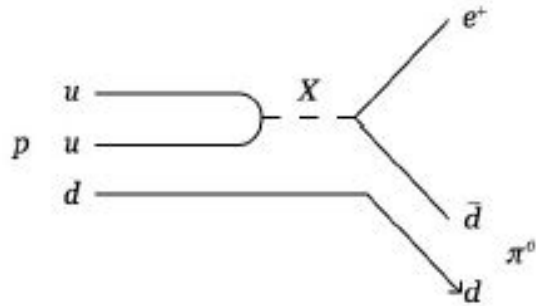
- B, L conservation \leftrightarrow accidental symmetries
 - Violation in SM extensions, eg supersymmetry
 - Violation in non-perturbative EW SM (eg spalerons)
- BNV needed for baryogenesis.
 - proton is stable, where is the BNV ?
- Explore selection rules:

$$\Delta B \neq 0, \Delta L = 0, \Delta(B - L) \neq 0 \quad [n \rightarrow \bar{n}, n \rightarrow n']$$

$$\Delta B = 0, \Delta L \neq 0, \Delta(B - L) \neq 0 \quad [0\nu 2\beta]$$

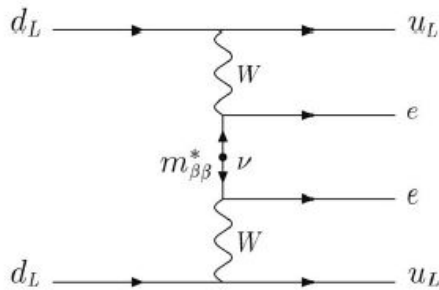
$$\Delta B \neq 0, \Delta L \neq 0, \Delta(B - L) = 0 \quad [p \text{ decay}]$$

Complementary BNV, LNV observables



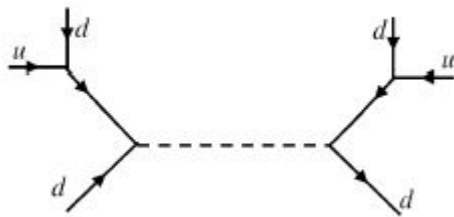
$$p \rightarrow e^+ + \pi^0$$

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



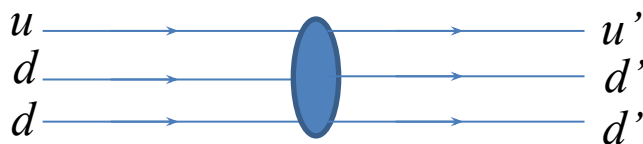
$$0\nu 2\beta$$

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



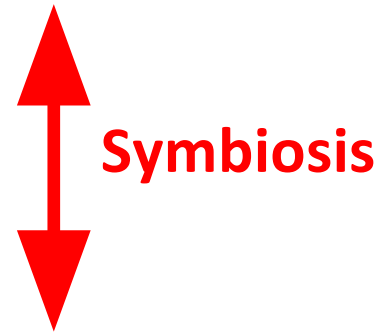
$$n \rightarrow \bar{n}$$

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



$$n \rightarrow n' \text{ (mirror)}$$

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



Looking for BNV

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

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

(RPP)

| | |
|---|--------------------|
| $p \rightarrow e^+ \gamma$ | > 670 |
| $p \rightarrow \mu^+ \gamma$ | > 478 |
| $n \rightarrow \nu \gamma$ | > 28 |
| $p \rightarrow e^+ \gamma \gamma$ | > 100 |
| $n \rightarrow \nu \gamma \gamma$ | > 219 |
| $p \rightarrow e^+ e^+ e^-$ | > 793 |
| $p \rightarrow e^+ \mu^+ \mu^-$ | > 359 |
| $p \rightarrow e^+ \mu \nu$ | > 170 |
| $n \rightarrow e^+ e^+ \nu$ | > 257 |
| $n \rightarrow \mu^+ e^+ \nu$ | > 83 |
| $n \rightarrow \mu^+ \mu^+ \nu$ | > 79 |
| $p \rightarrow \mu^+ e^+ e^-$ | > 529 |
| $p \rightarrow \mu^+ \mu^+ \mu^-$ | > 675 |
| $p \rightarrow \mu^+ \mu \nu$ | > 220 |
| $p \rightarrow e^+ \mu^+ \mu^+$ | > 6 |
| $n \rightarrow 3\nu$ | > 0.0005 |
| $N \rightarrow e^+ \text{anything}$ | > 0.6 (n, p) |
| $N \rightarrow \mu^+ \text{anything}$ | > 12 (n, p) |
| $N \rightarrow e^+ \pi^0 \text{anything}$ | > 0.5 (n, p) |
| $pp \rightarrow \pi^+ \pi^+$ | > 0.7 |
| $pn \rightarrow \pi^+ \pi^0$ | > 2 |
| $nn \rightarrow \pi^+ \pi^-$ | > 0.7 |
| $nn \rightarrow \pi^0 \pi^0$ | > 3.4 |
| $pp \rightarrow K^+ K^+$ | > 170 |
| $pp \rightarrow e^+ e^+$ | > 5.8 |
| $pp \rightarrow e^+ \mu^+$ | > 3.6 |
| $pp \rightarrow \mu^+ \mu^+$ | > 1.7 |
| $pn \rightarrow e^+ \bar{\nu}$ | > 2.8 |
| $pn \rightarrow \mu^+ \bar{\nu}$ | > 1.6 |
| $pn \rightarrow \tau^+ \bar{\nu}_\tau$ | > 1.0 |
| $nn \rightarrow \nu_e \bar{\nu}_e$ | > 1.4 |
| $nn \rightarrow \nu_\mu \bar{\nu}_\mu$ | > 1.4 |

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

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

Few BNV -only searches

Last search for free
 $n \rightarrow \bar{n}$ in 1990's.

If nature chooses $\Delta B \neq 0, \Delta L = 0$

→ difficult to observe

→ Baryon decays need a lepton for angular momentum conservation

→ BNV -only observables are fragile:

$n \rightarrow \bar{n}$ suppressed for non-free neutrons.

BNV-only observables at HIBEAM

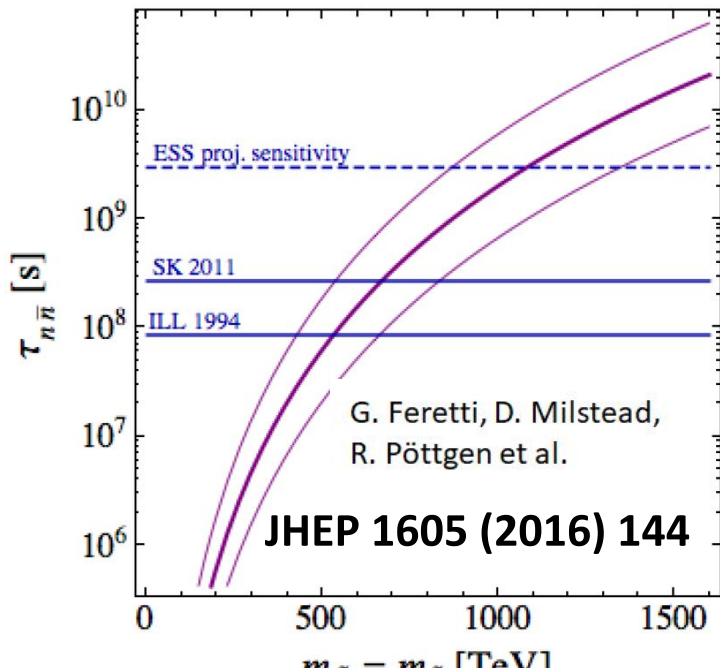
$$n \rightarrow \bar{n} (\Delta B = 2)$$

RPV SUSY, PeV-scale

Lepton-quark unification, $0\nu 2\beta$

GUT-scale

Post-sphaleron baryogenesis

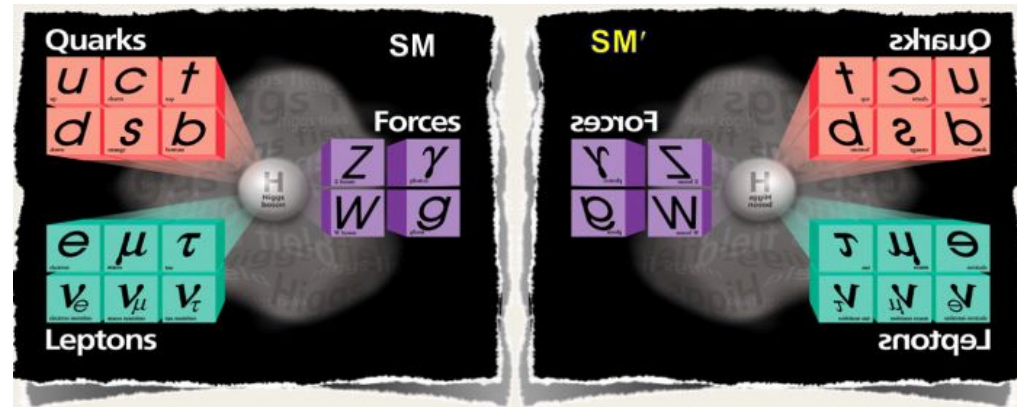


$$n \rightarrow n' (\Delta B = 1)$$

Mirror matter - parity symmetry, $Q=0$
particles can mix with a "dark" sector

Dark matter

Resolve neutron lifetime anomaly



European Spallation Source

High intensity spallation source

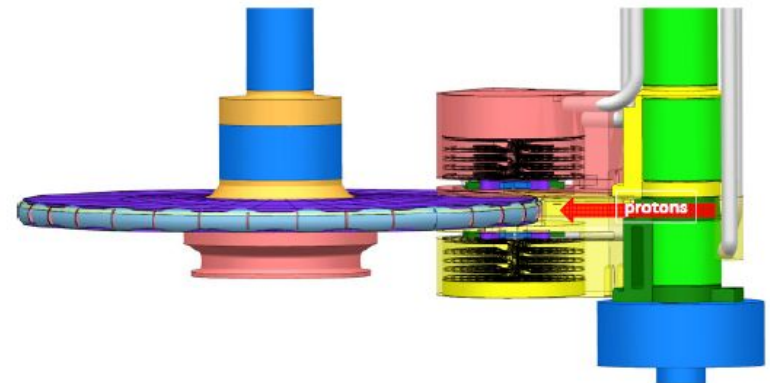
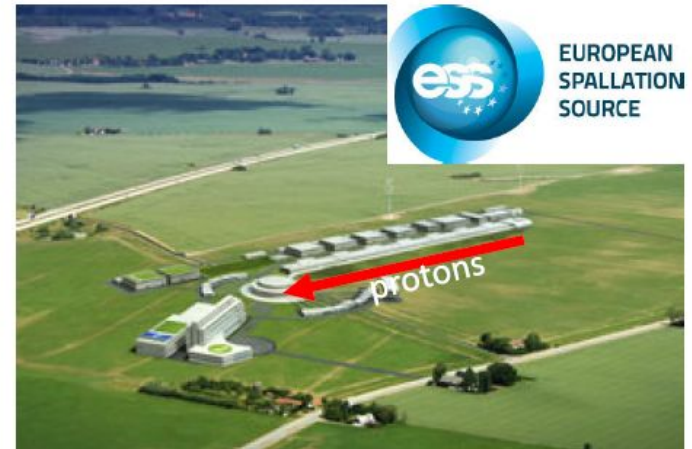
Multi-disciplinary research centre –
17 European nations

Lund, Sweden

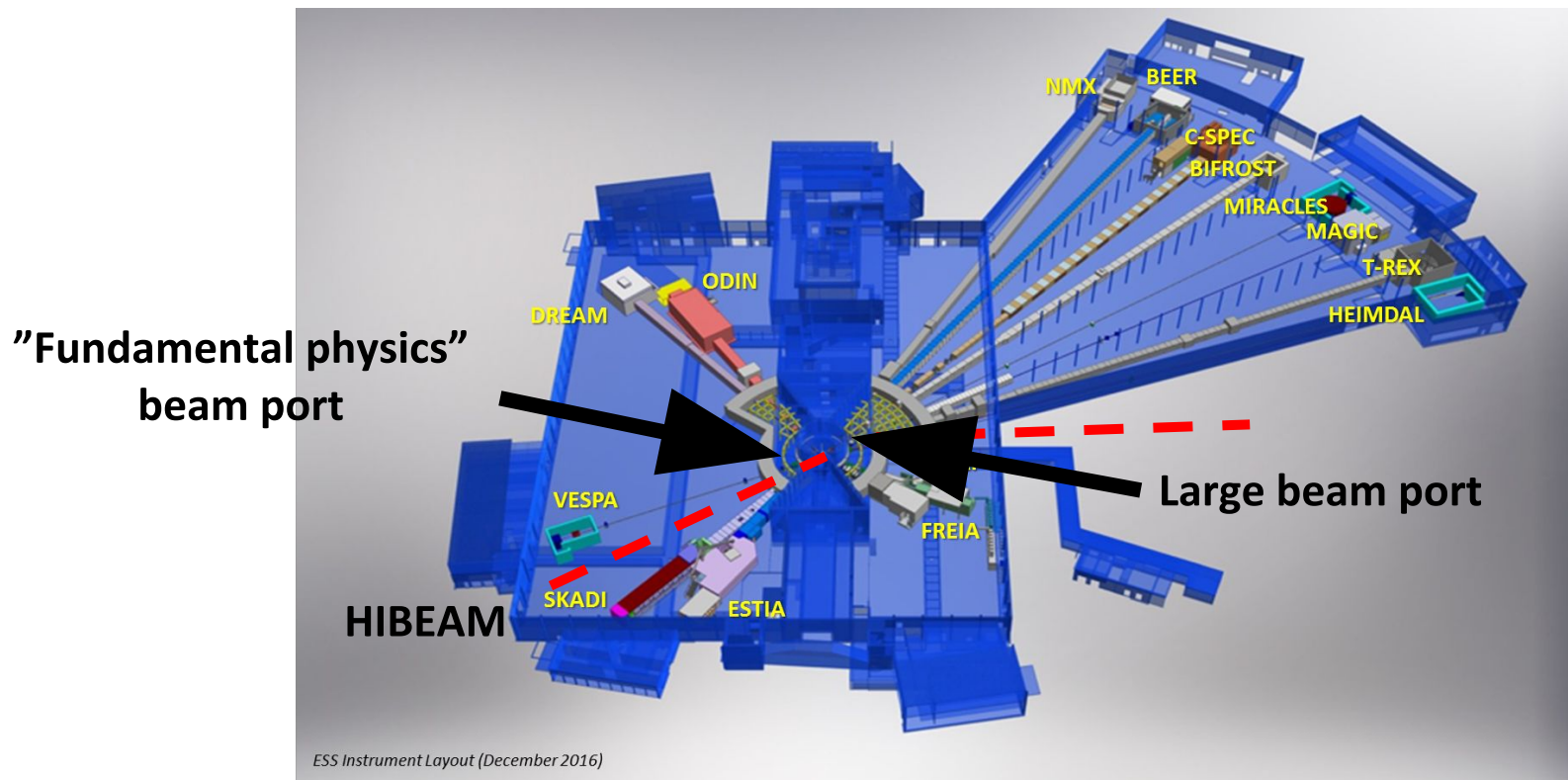
Early physics ~2023/2024

2 GeV protons (3ms long pulse, 14
Hz) on rotating Tungsten target.

Neutrons slowed by moderator and
dispatched via beam-ports to expts.



Fundamental physics at the ESS



Plan for "fundamental physics" beam port for HIBEAM
Large Beam Port for full expt.

The proposed program

Stage 1

HIBEAM - high intensity baryon extraction and measurement

Early to late 2020s

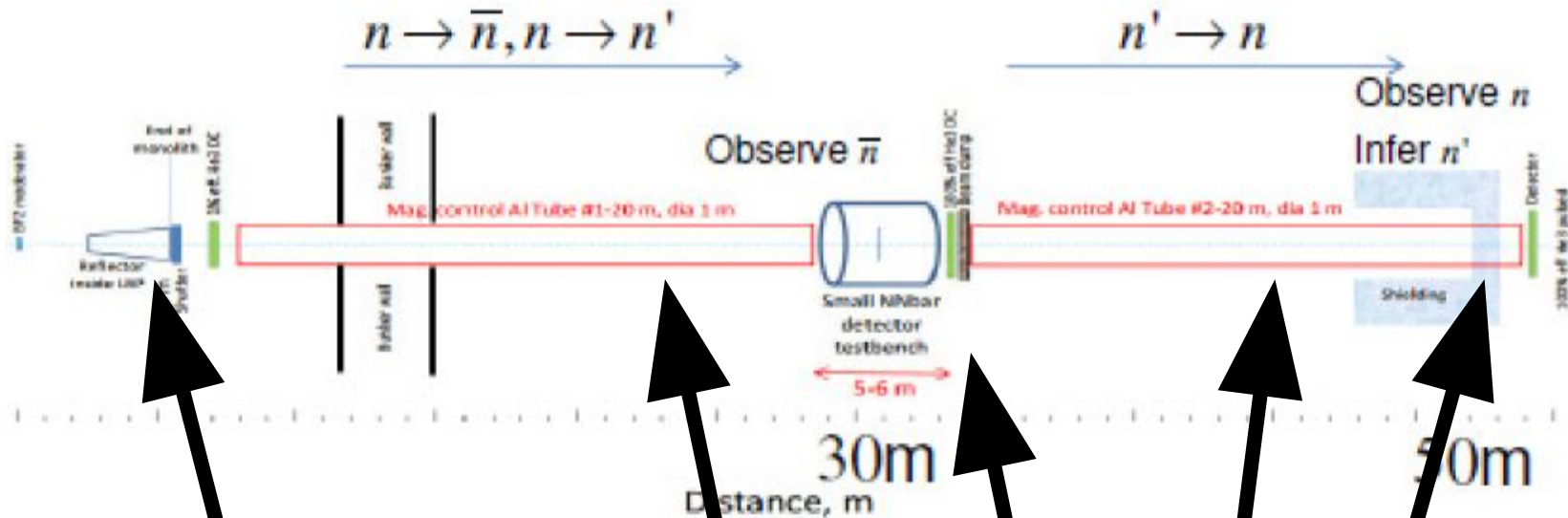
- Match or improve sensitivity to $P(n \rightarrow \bar{n})$ wrt previous search at ILL
- Search for mirror neutrons (regeneration)
- R&D for full experiment (*NNBAR*)

Stage 2

Late 2020's + 5 years

- Improve sensitivity to $P(n \rightarrow \bar{n})$ by $\sim 10^3$
- Further mirror neutron searches

HIBEAM

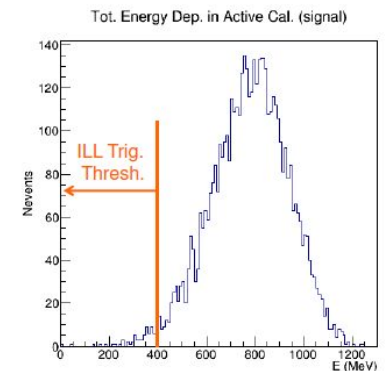
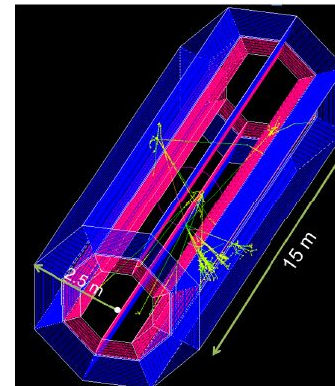
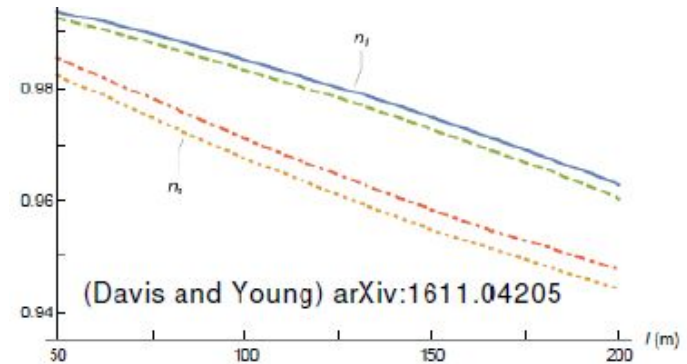
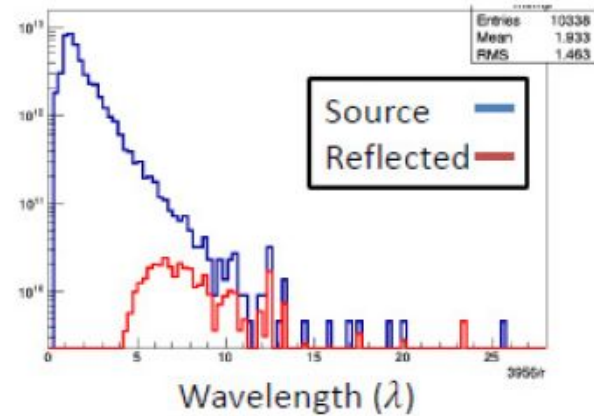


1. Neutron focusing
2. Passage through shielded tube
3. If $n \rightarrow \bar{n} \rightarrow$ annihilation of \bar{n} in C target
4. If $n \rightarrow n' \rightarrow$ passage through absorber
5. $n' \rightarrow n \rightarrow$ measure n in neutron counter

300m long beam tube planned for full NNBAR experiment.

Activities

- Neutronics
 - Optics to match moderator
- Radiation Shielding
 - BG suppression
- Magnetic shielding
 - tolerable field (30nT)
- Detector simulation
 - Tracker, calo + scintillators



HIBEAM and ESS

HIBEAM

Six workshops (CERN, Lund, Gothenburg, Copenhagen)
Expression of Interest 2015.

26 institutes, 8 countries.

Co-spokespersons : G. Broojimans, D. Milstead

Lead scientist: Y. Kamyskov

Sweden: SU,UU,LU,Chalmers

ESS

No fundamental physics instrument from first call

Wish from ESS management for fundamental physics –
new call 2018

Plan to submit a joint proposal with ANNI collaboration
in 2018.

Successful application → 10-14 Meuros.

Neutron-Anti-Neutron Oscillations at ESS
Lund, Feb 18-19, 2015

Several particle oscillations have proven to be extremely valuable practical fundamental physics. Some oscillations predicted by early 20th century quantum field theory, but by neutrinos provided the first evidence for the top quark is relatively heavy. It oscillates between the most basic ground level and excited states of 3D oscillation and neutrinos oscillations suggest the existence of a new important energy scale well below the GUT scale. Neutrinos oscillating and antineutrinos will offer a unique probe of beyond standard model physics.

The construction of the European Spallation Source (ESS) will not only be the largest accelerator facility together with current nuclear optical facilities, offers an opportunity to conduct an experiment with a best class source of high-brightness neutrons and antineutrons in the nucleus oscillation probability.

As the oscillation physics is used for such an experiment will be discussed together with the main experimental challenges and possibilities. We hope this workshop will contribute to the development of a collaboration to build and perform the experiment.

Organizing committee:

- 1. Bengt Aronsson
- 2. Erik Eriksson
- 3. Erik Eriksson
- 4. Erik Eriksson
- 5. Erik Eriksson
- 6. Erik Eriksson
- 7. Erik Eriksson
- 8. Erik Eriksson
- 9. Erik Eriksson
- 10. Erik Eriksson

Register before 18 May at
www.essex.ac.uk/ess

Summary

- Observation of baryon number violation would be of fundamental significance.
- Nature makes BNV-only observables hard to find and measure
 - Last $n \rightarrow \bar{n}$ search in 1990's.
- Unique opportunity for high sensitivity searches for $n \rightarrow \bar{n}$, $n \rightarrow n'$ at ESS
- HIBEAM is first stage of project to improve sensitivity to $P(n \rightarrow \bar{n})$ by $\sim 10^3$.
- Collaboration preparing a proposal for ESS in 2018
- *Follows the European Particle Strategy of supporting a set of experiments with complementary and unique physics reach.*