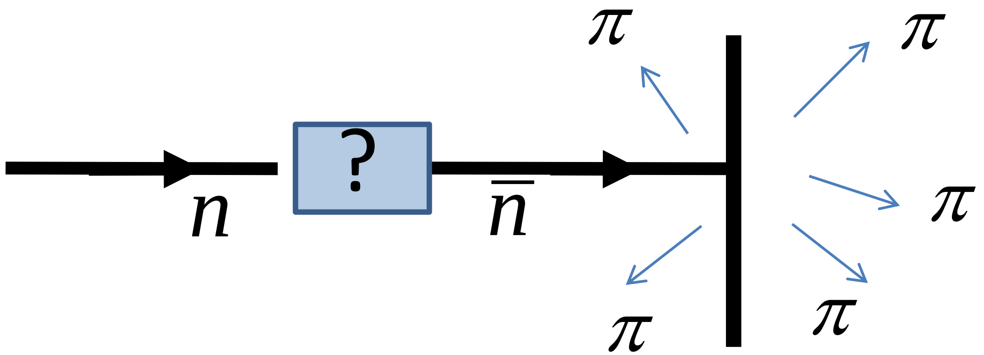
The HIBEAM Experiment for the European Spallation Source



D. Milstead
Stockholm University

Outline

1. The aims of the experiment
2. The physics case
3. The proposed program at the ESS
4. Status

HIBEAM

High Intensity Baryon Extraction and Measurement

Search for

- $n \to \bar{n}$
- $n \to n'$ (mirror neutrons)

Also measurements of weak nucleon-nucleon interactions.

Baryon and lepton number violation

- *BN,LN* "accidental" SM symmetries at perturbative level
  - *BNV, LNV* in SM non-perturbatively (eg instantons)
  - *B-L* is conserved, not *B, L* separately.

- *BNV, LNV* needed for baryogenesis and leptogenesis

- *BNV,LNV* generic features of SM extensions (eg SUSY)

$n \rightarrow \bar{n}$

- Dimensional reasoning:

$6q$ operator for $\Delta B = 2, \Delta L = 0 \Rightarrow \delta m_{n\to\bar{n}} = \dfrac{c\Lambda_{QCD}^{6}}{M^{5}} \Rightarrow M \sim 1000$ TeV

- R-parity violating supersymmetry
- Unification theories: $M \sim 10^{15}$ GeV
- Extra dimensions models
- Post-sphaleron baryogenesis
- etc, etc: [arXiv:1410.1100]

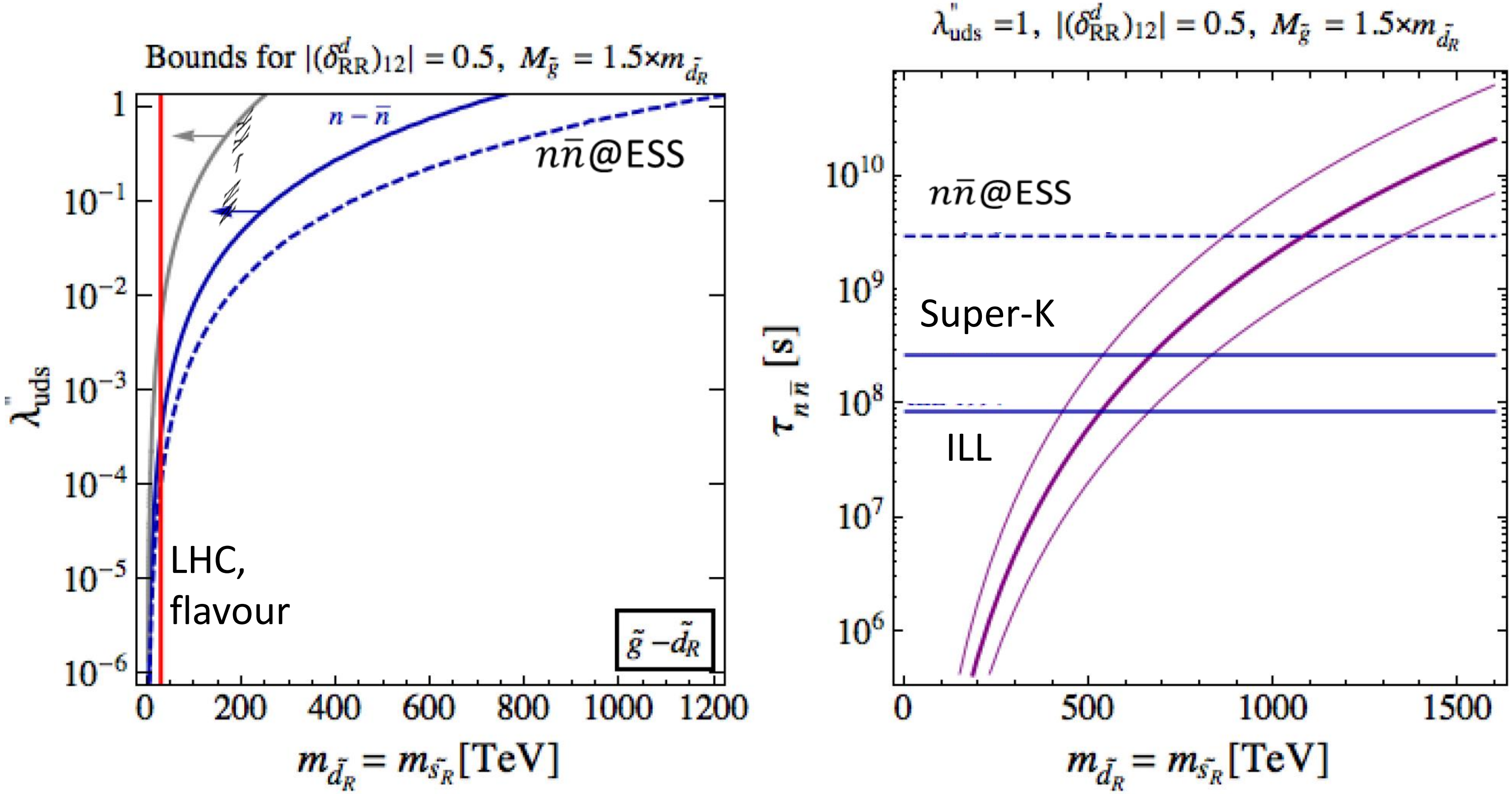
High precision $n \to \bar{n}$ search

$\Rightarrow$ Scan over wide range of phase space for generic BNV

+

$\Rightarrow$ model constaints.

RPV-SUSY



Constraints vanish for >> TeV masses

nnbar@ESS: extends mass range by up to ~400 TeV cf Super-K

: pushes into the PeV scale

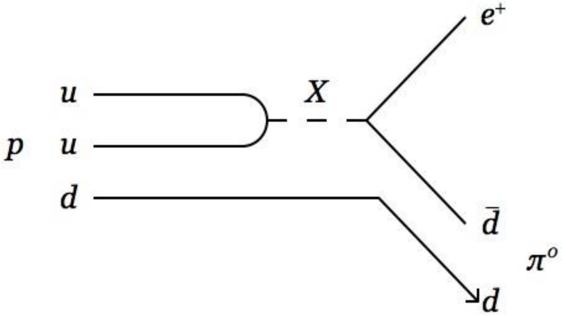
Complementary B,L-violation observables

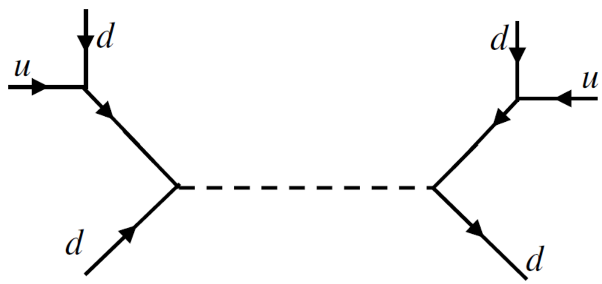
$\Delta B = \Delta L = 1,$
$\Delta(B-L) = 0$

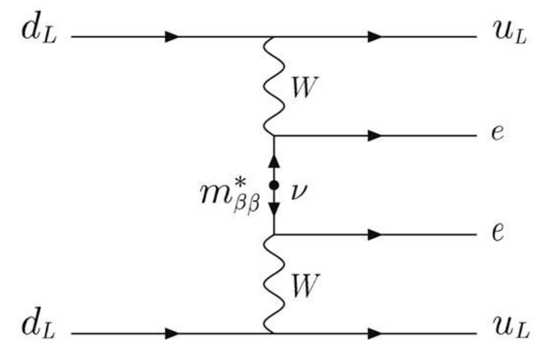
$\Delta B = 2, \Delta L = 0,$
$\Delta(B-L) = 2$

Symbiosis

$\Delta B = 0, \Delta L = 2,$
$\Delta(B-L) = 2$







Nucleon decay

$n \to \bar{n}$, NN decay.

Stable proton.

Few pure BNV searches

$0\nu\beta\beta$

Neutron oscillations – an experimentalist's view

Hypothesis: baryon number is weakly violated.

How do we look for BNV?

Single nucleon decay searches, eg, $p \to \pi^0 + e^+$?
$\Rightarrow$ L-violation, another (likely weakly) violated quantity.

Decays without leptons, eg, $p \to \pi + \pi,$ impossible due to angular momentum conservation.

Nature may well have chosen BNV albeit with few processes to observe it.

$n \to \bar{n}$ and dinucleon decay searches sensitive to BNV-only processes.
Free $n \to \bar{n}$ searches $\Rightarrow$ cleanest experimental and theoretical approach.

Previous searches for BNV

(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)
$pp \to \pi^+\pi^+$ (highlighted yellow)	> 0.7
$pn \to \pi^+\pi^0$ (highlighted yellow)	> 2
$nn \to \pi^+\pi^-$ (highlighted yellow)	> 0.7
$nn \to \pi^0\pi^0$ (highlighted yellow)	> 3.4
$pp \to K^+K^+$ (highlighted yellow)	> 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

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

Limits on τ_{life} from all searches

$\sim 10^{30} - 10^{34}$ yrs

$\Delta B \neq 0, \Delta L \neq 0$ (blue)

$\Delta B \neq 0, \Delta L = 0$ (yellow)

New experiment: $\Delta B \neq 0, \Delta L = 0$

τ_{life} sensitivity $\sim 10^{35}$ yrs

Discovery or new stringent limit on stability of matter.

$n \rightarrow \bar{n}$ 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

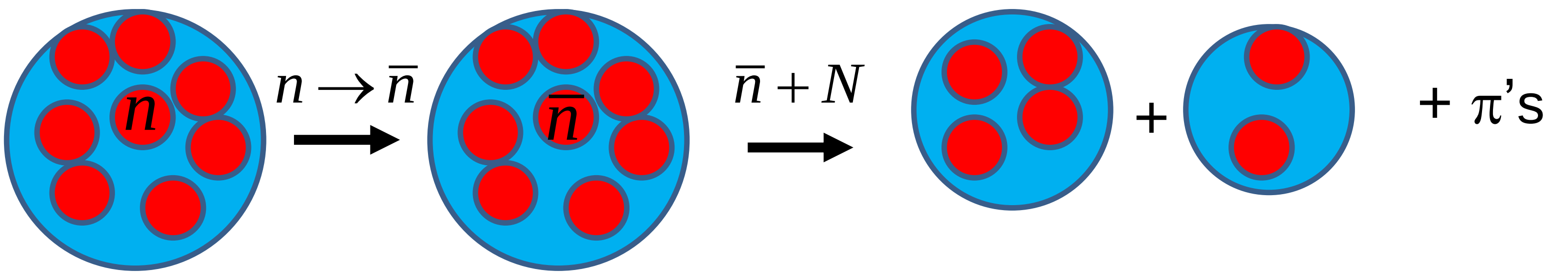
$$P_{n\rightarrow\bar{n}} = \left(\frac{\delta m}{\Delta E}\right)^2 \sin^2\left(\Delta E \times t\right) \;\; ; \; \Delta E = E_n - E_{\bar{n}}$$

Two interesting cases:

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

Suppression of $n \rightarrow \bar{n}$

Nuclear disintegration after neutron oscillation



$$P_{n \rightarrow \bar{n}} = \left(\frac{\delta m}{\Delta E}\right)^2 \sin^2\left(\Delta E \times t\right) ,$$ ΔE □ 100 MeV $\Rightarrow$ Suppression: $\left(\frac{\delta m}{\Delta E}\right)^2 < 10^{-60}00$

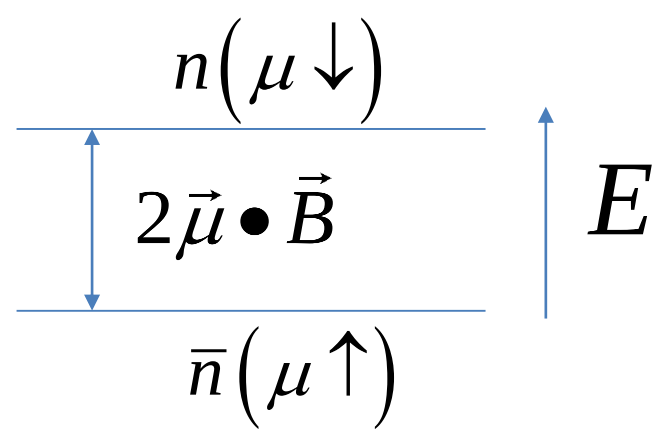
Best current limits (SuperKamiokande) $\Rightarrow$ $\tau_{free} > 2.5 \times 10^8$ s

Irreducible bg's prevent large improvements. Model-dependent (nuclear interactions).

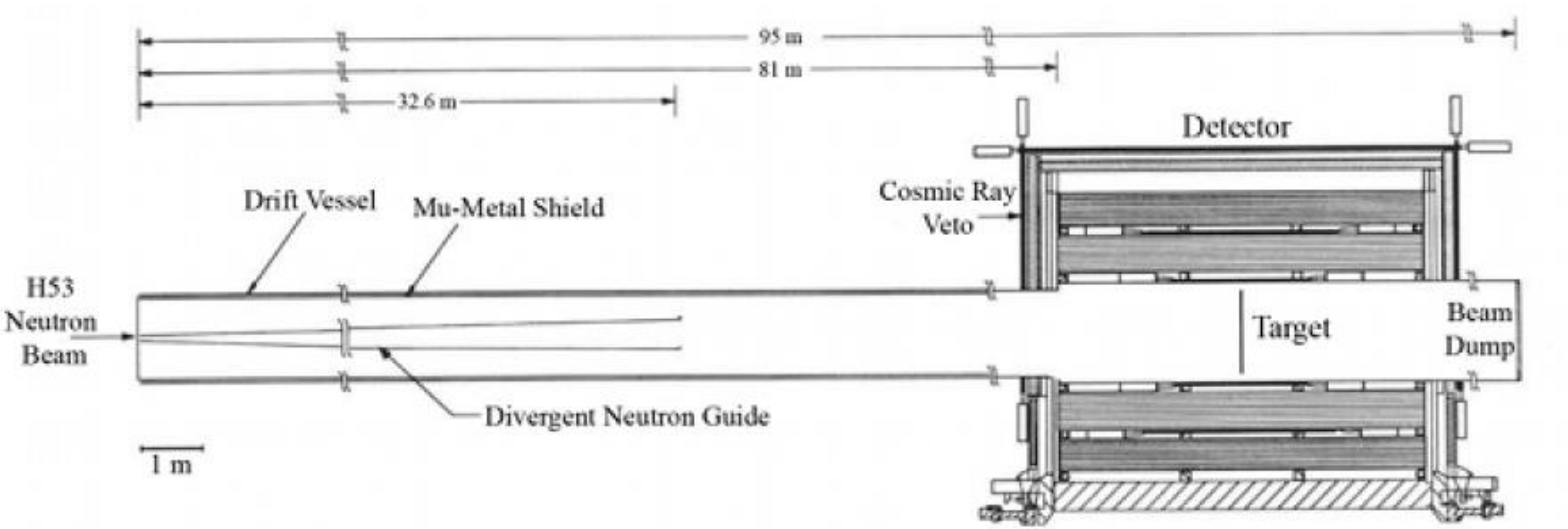
Neutron oscillation in a magnetic field

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

$\Rightarrow$ suppression.



Free neutron search at ILL



Institute Laue-Langevin (Early 1990's).

Cold neutron beam from 58MW reactor.

 130μm thick carbon target

Signal of at least two tracks with $E > 850$ MeV

0 candidate events, 0 background.

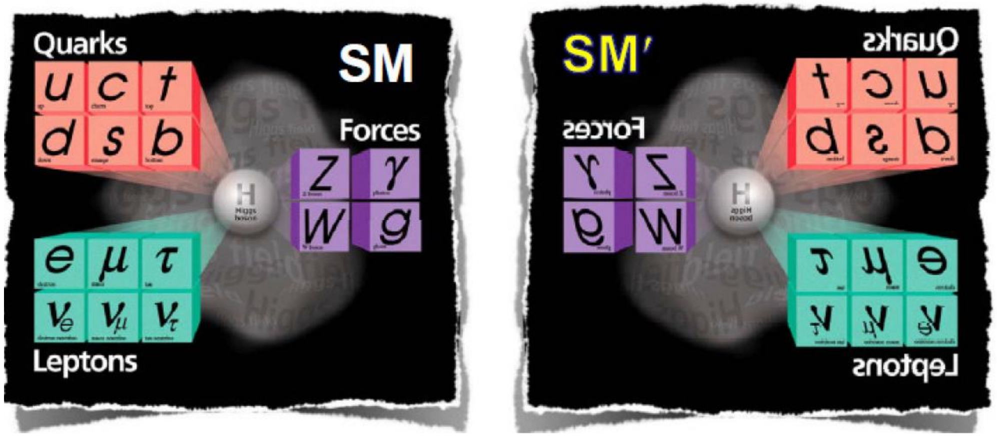
$\Rightarrow \tau_{n\to\bar{n}} > 0.86\times 10^{8}$ s.

Mirror matter

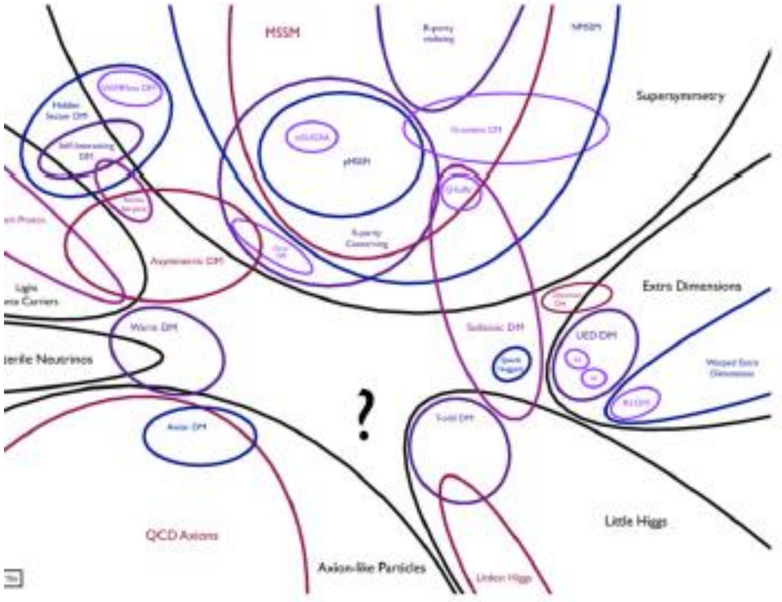
Hidden/mirror sector

Restores partity symmetry

Possible mixing for $Q = 0$ particles

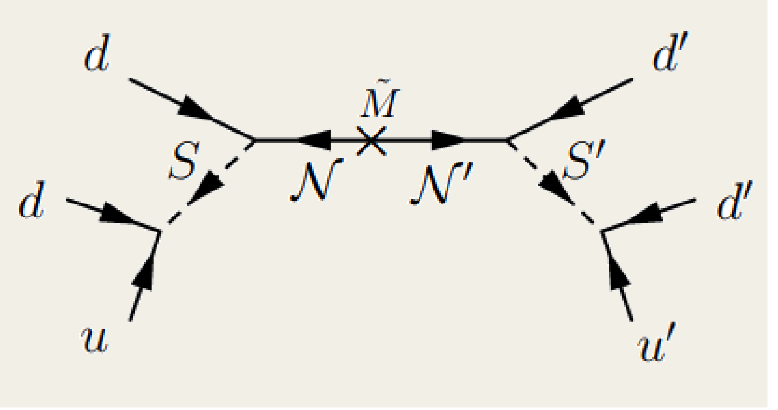


Mirror matter - dark matter candidates.

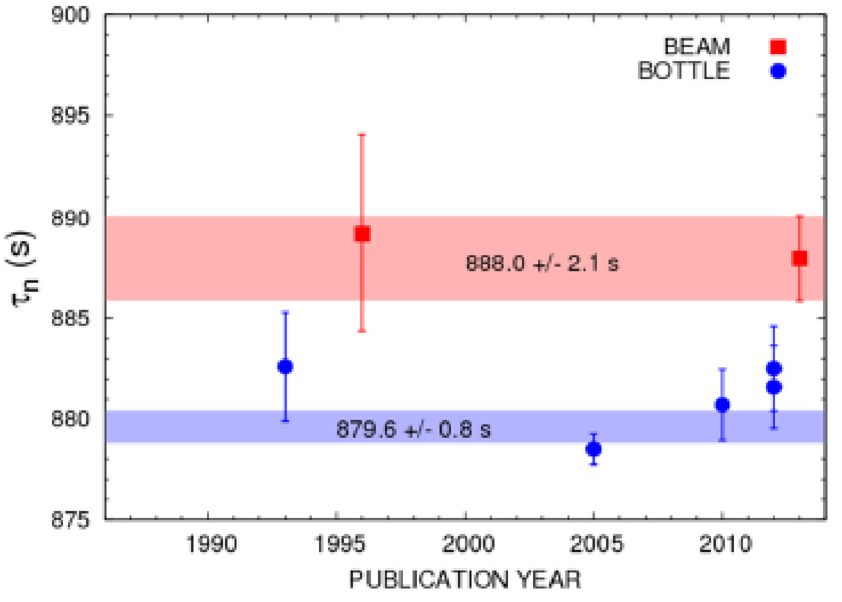


Mirror neutrons

$$n \rightarrow n'$$



Can explain 5σ discrepancy between neutron lifetime measurements with bottle and beam methods.



Search made with stored ultra-cold neutrons: τ>12s for $B < 125$ mG

Outline

1. The aims of the experiment ✓
2. The physics case ✓
3. The proposed program at the ESS
4. Status

The European Spallation Source

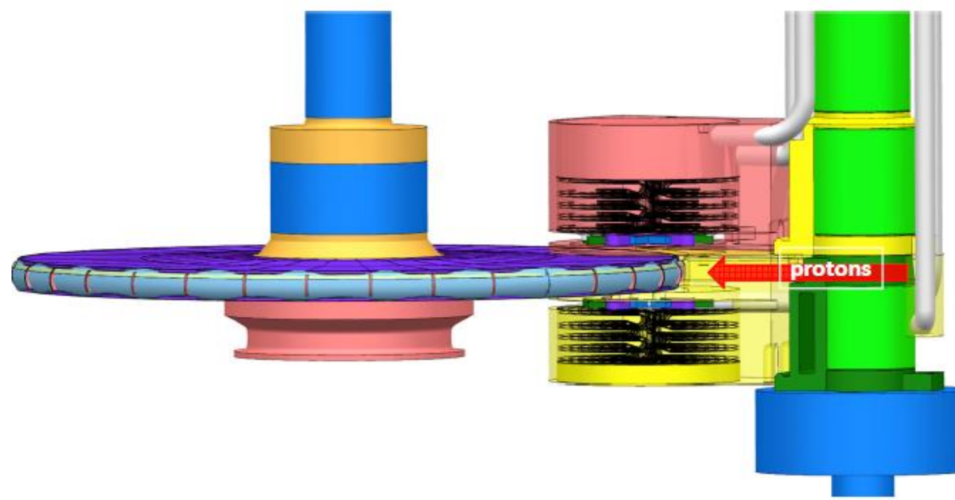
High intensity spallation
neutron source

Multidisplinary research centre
with 17 European nations
participating.

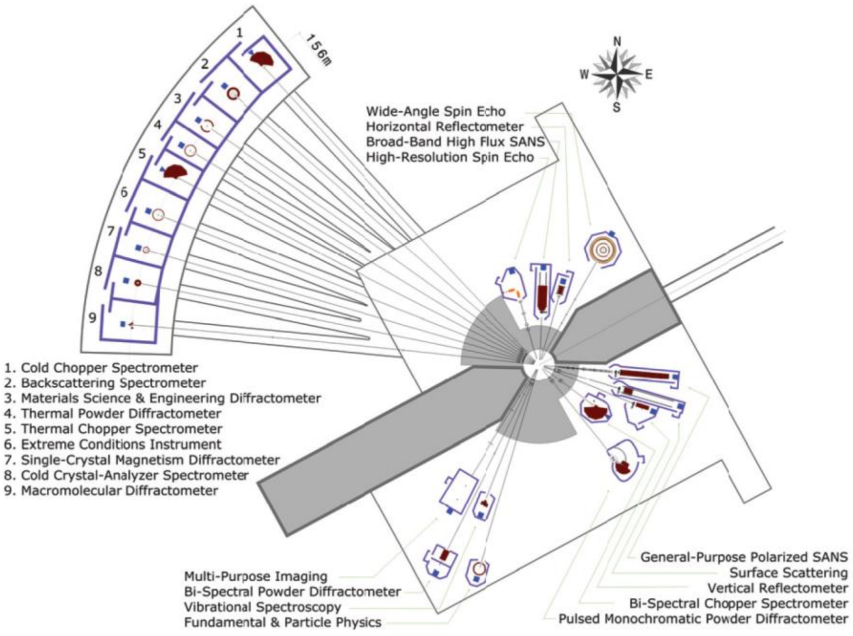
Lund, Sweden.
Start operations in 2019.

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

Cold neutrons after interaction with moderators.

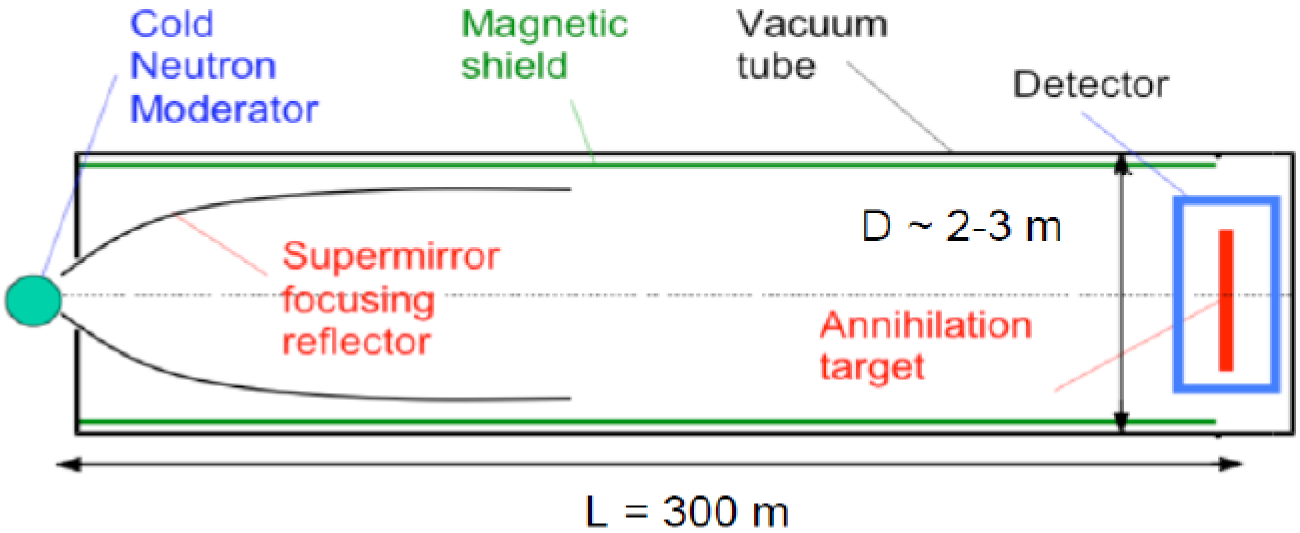


The European Spallation Source



 22 instruments/experiments with capability for more.

Search for $n \to \bar{n}$

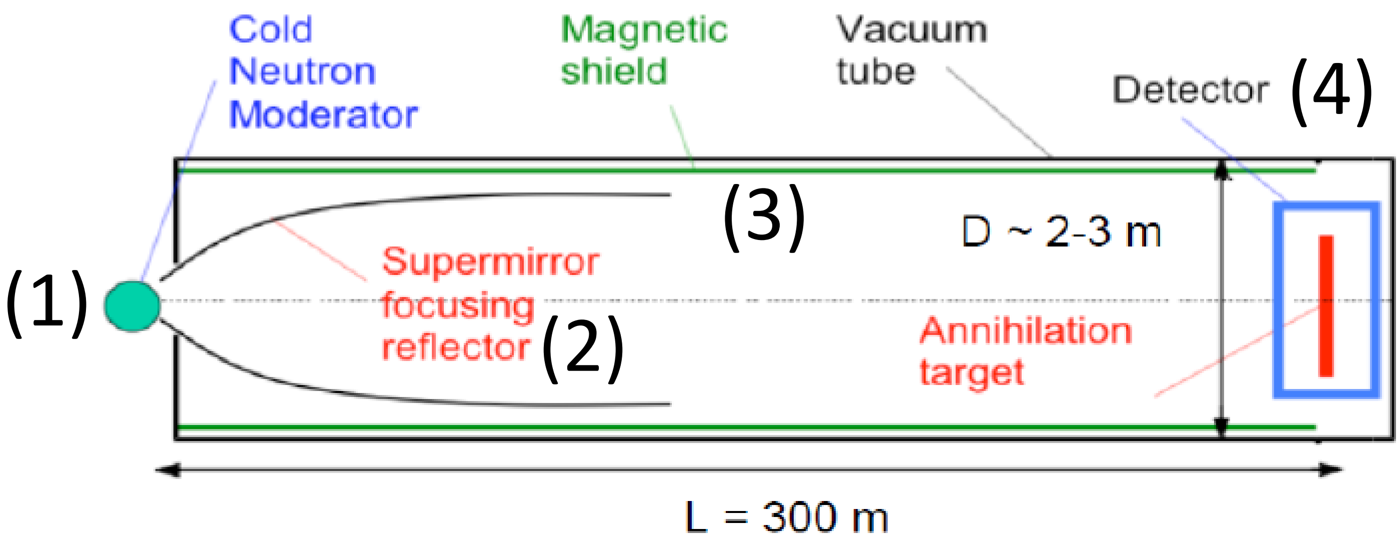


Sensitivity = (free neutron flux at target) $\times P(n \to \bar{n}) \propto N_n t^2$

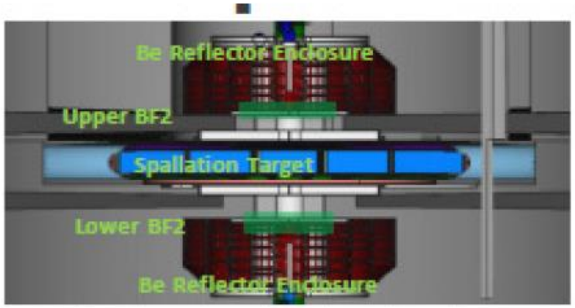
- Cold neutrons (E<5 meV, v<1000ms^{-1})
- Low neutron emission temperature (50-60 K)
- Supermirror transmission and transit time
- Large beam port option, large solid angle to cold moderator.

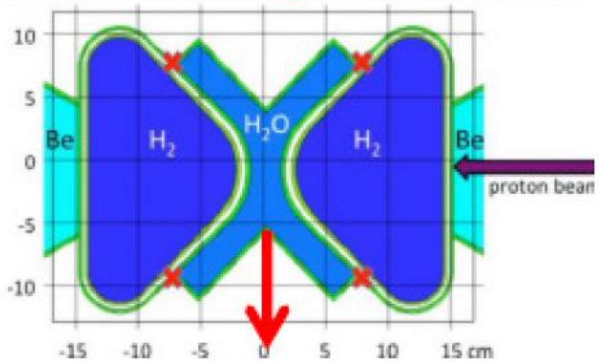
Increase in sensitivity for $P_{n\bar{n}}$ ~ 10^3 compared to previous experiment (ILL)

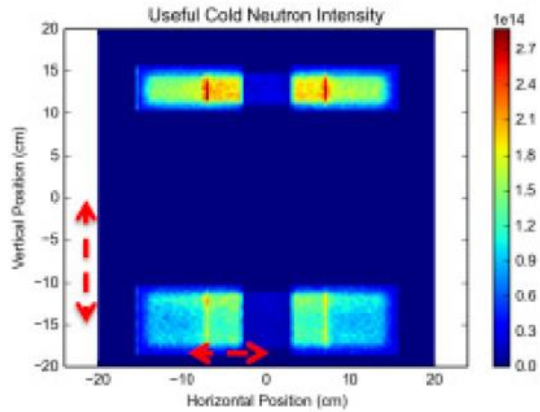
- Neutron guiding, larger opening angle, higher flux, particle ID technologies, running time.

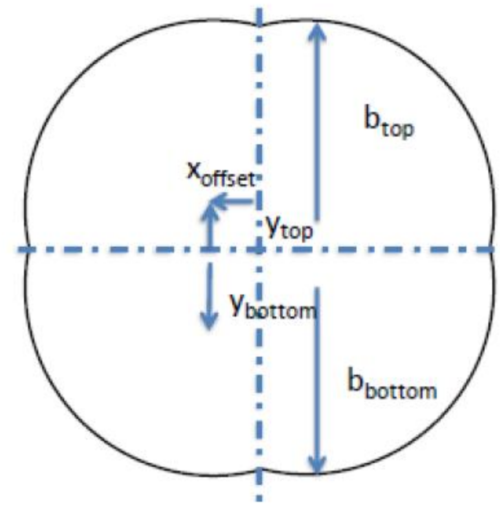

Cold
Neutron
Moderator
Magnetic
shield
Vacuum
tube
Detector
(4)
(3)
D ~ 2-3 m
(1)
Supermirror
focusing
reflector
(2)
Annihilation
target
L = 300 m

Moderator/neutronics









"Butterfly" hybrid moderator for thermal and cold neutrons.

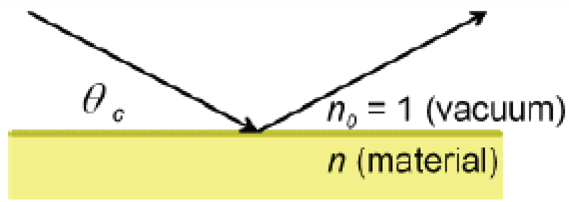
ESS to start with only upper moderator.

Eg "Lobed" quadruple focusing

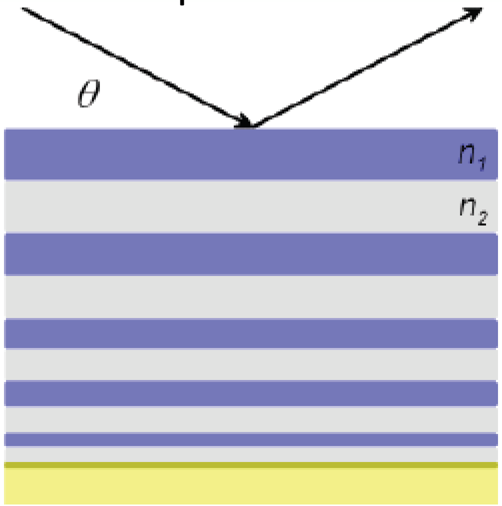
Different neutron focusing options being studied.

Neutron supermirror

Smooth surface

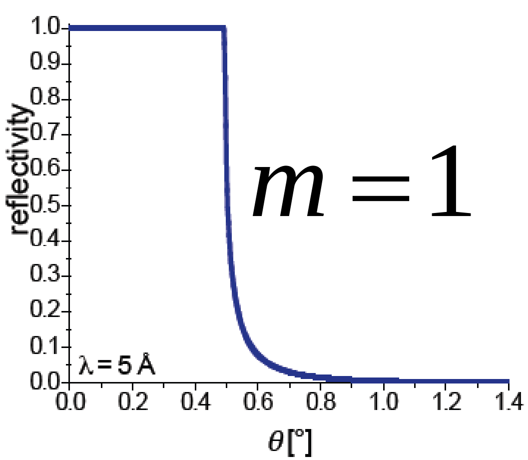


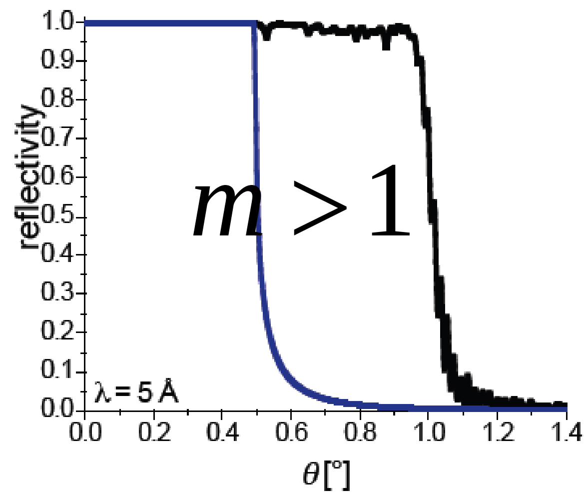
Supermirror



θ_c=Critical angle for total internal reflection

$\theta_c \rightarrow m\theta_C^{Ni}$





Need efficient focusing and minimal interactions (each interaction "resets the n-clock")

Neutron focusing

Achieve up to $m \sim 7$ supermirrors.

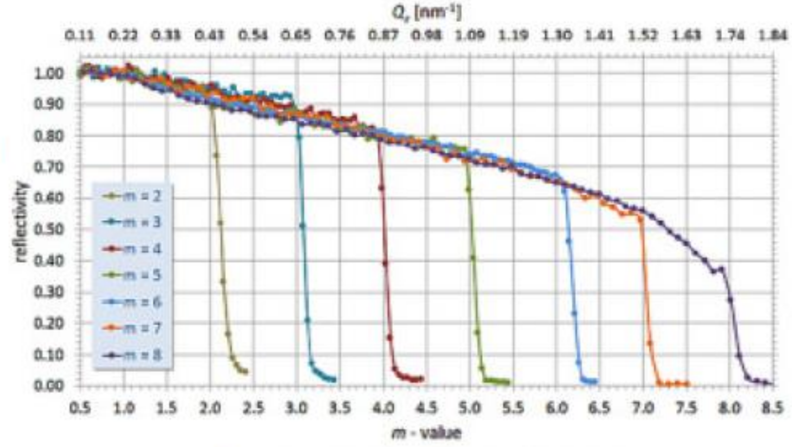
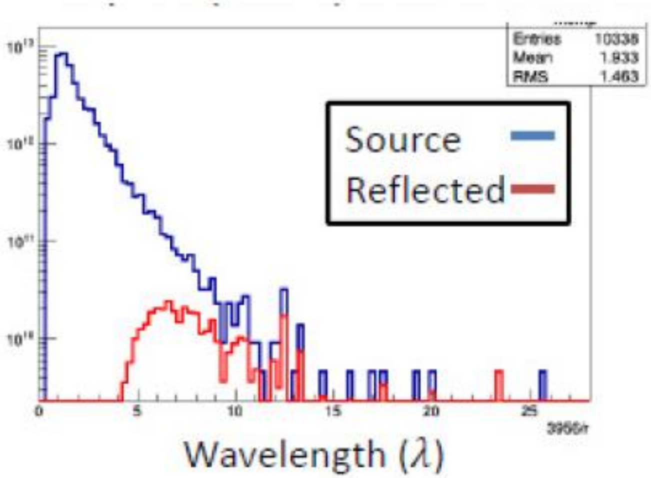
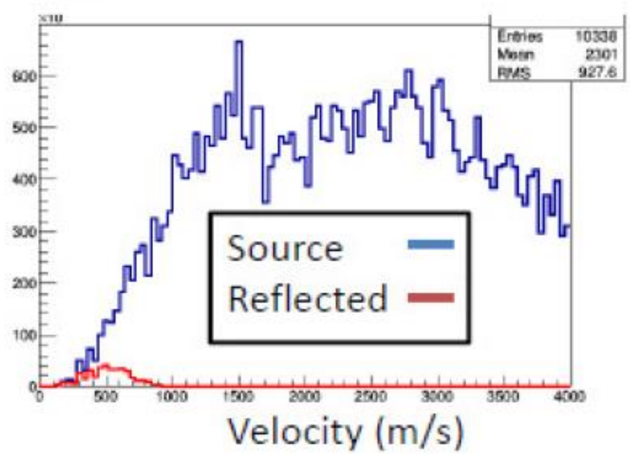
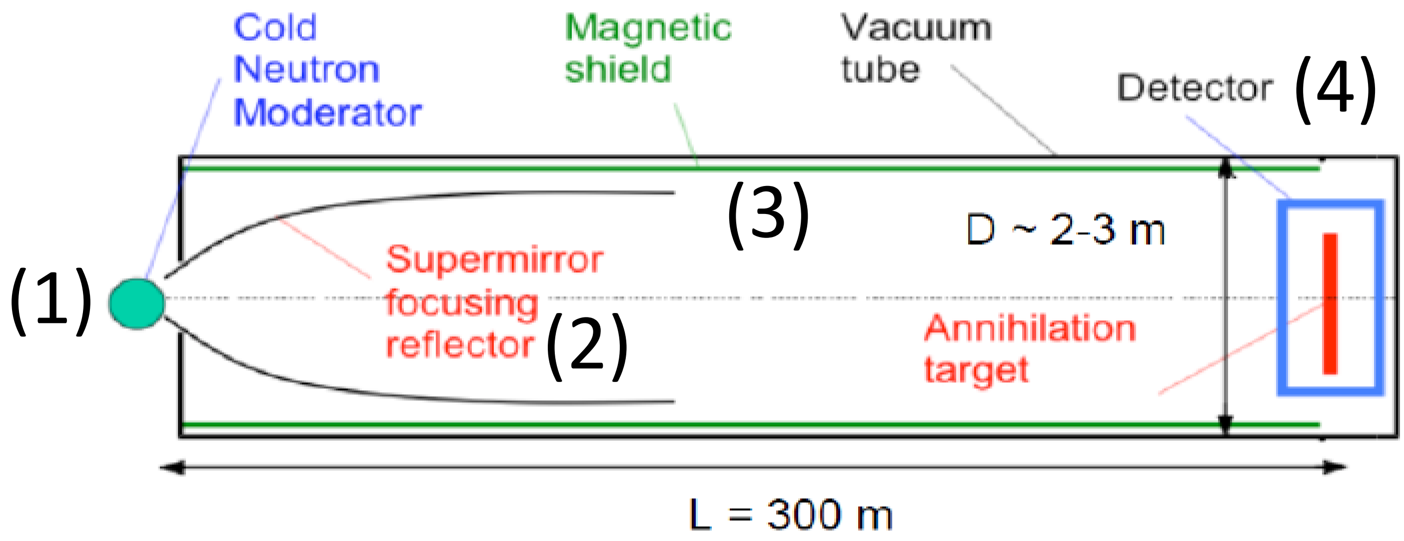


Figure 1: Reflectivity profiles of Ni/Ti & non-depolarising

Selectively focus cold neutrons

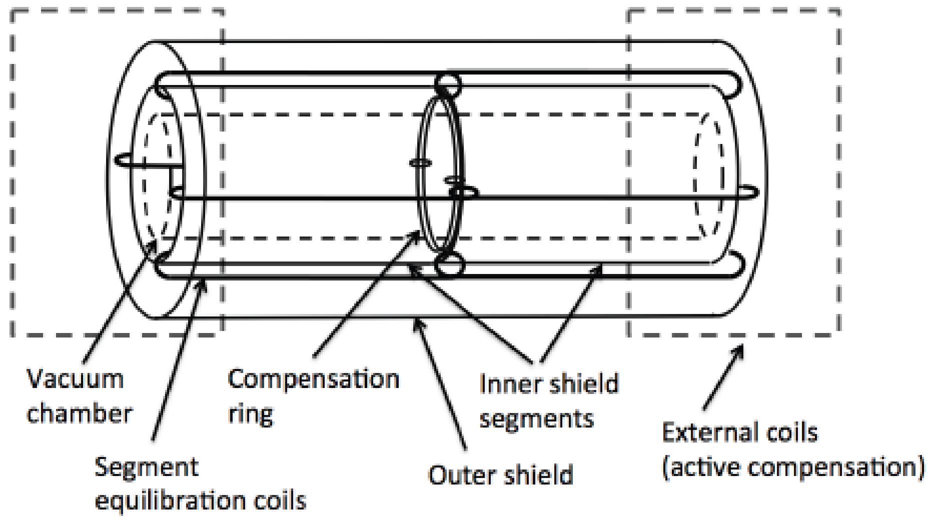






Cold
Neutron
Moderator
Magnetic
shield
Vacuum
tube
Detector
(4)
(3)
D ~ 2-3 m
(1)
Supermirror
focusing
reflector
(2)
Annihilation
target
L = 300 m

Shielding



Magnetic shielding for flight volume

- $B <$ 10nT, $P \sim 10^{-5}$mbar
- Aluminium vacuum chamber
- Passive magnetic shield from magnetizable alloy
- External coils for active compensation
- Background studied by turning on/off $\vec{B}$-field.

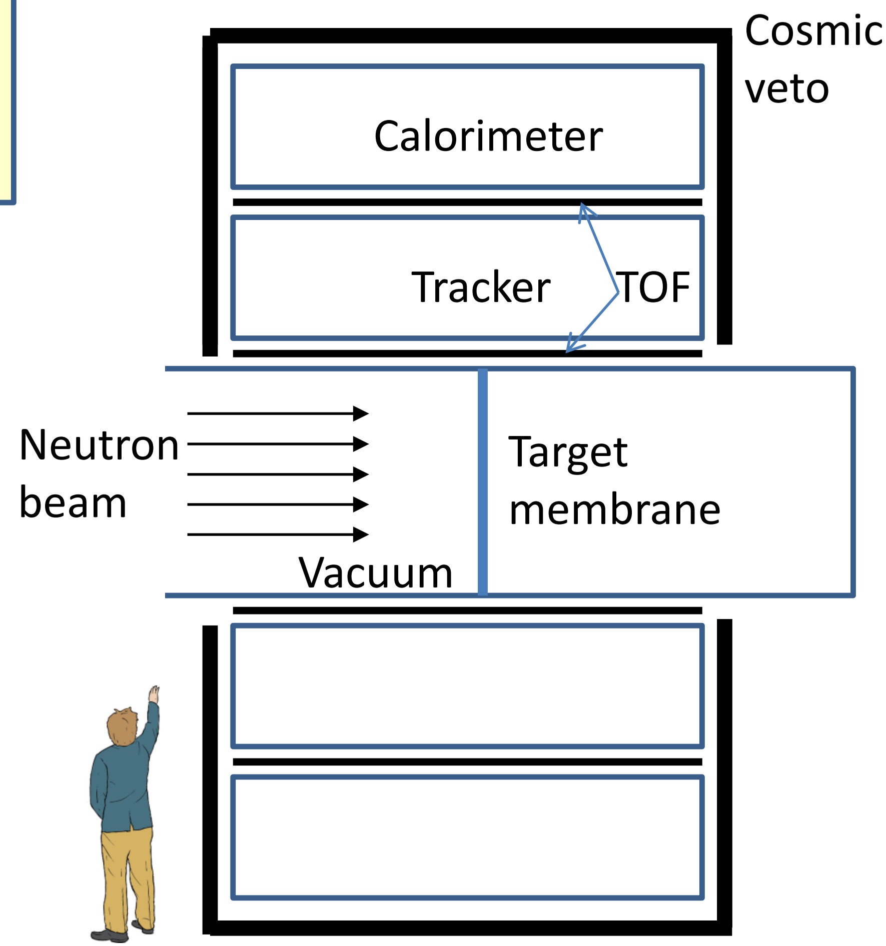
Detector

Expect $\bar{n} + N \rightarrow \sim 5\pi$ at $\sqrt{s} \approx 2$ GeV.

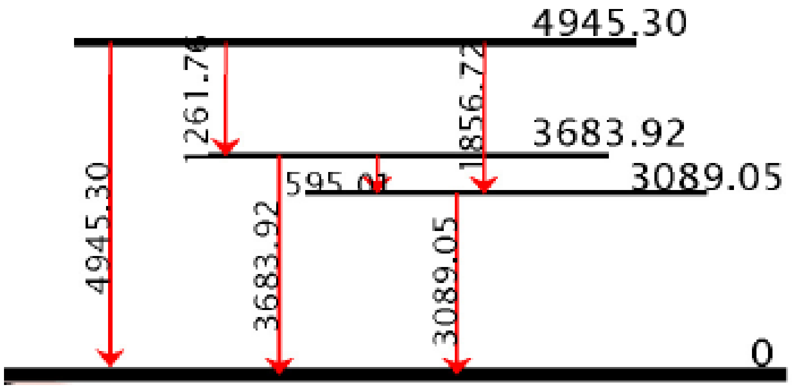
Detector design for high efficiency $(\varepsilon > 0.5)$

and low bg (≈ 0).

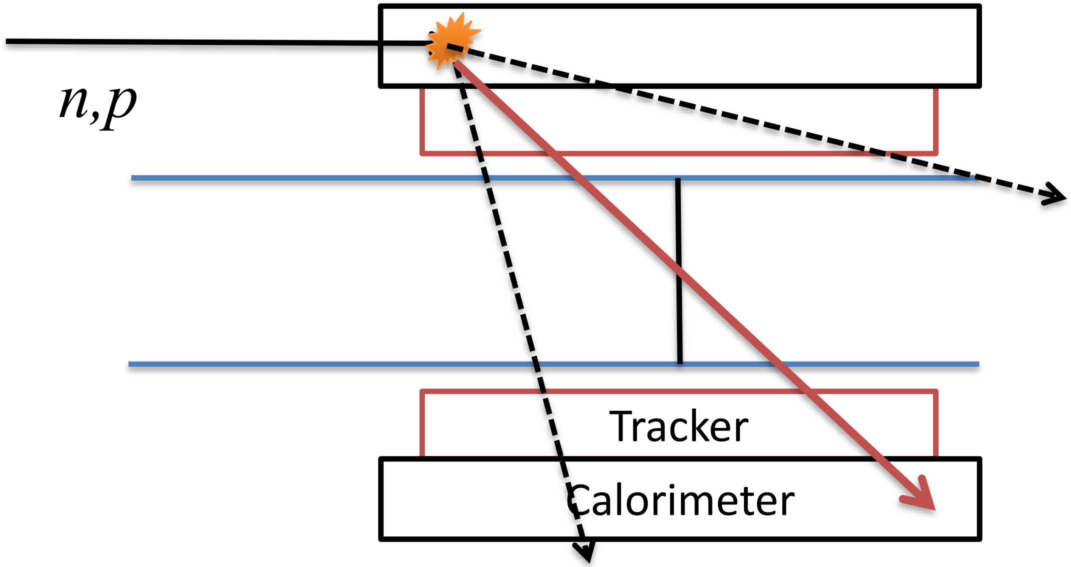
- Annihilation target - carbon sheet
- Tracker - vertex reconstruction
- Time-of-flight system
  - scintillators around tracker.
- Calorimeter
  - lead + scintillating and clear fibre.
- Cosmic veto - plastic scintillator pads
- Trigger - Track and cluster algorithms



Background Sources



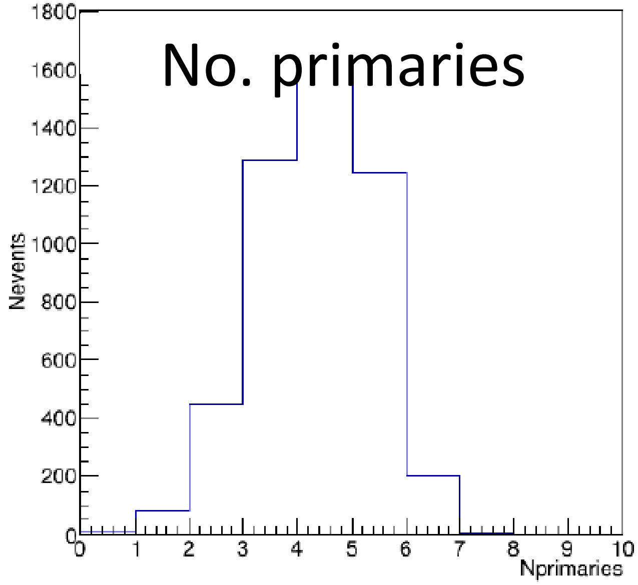
Capture γ from $n + {}^{12}C$

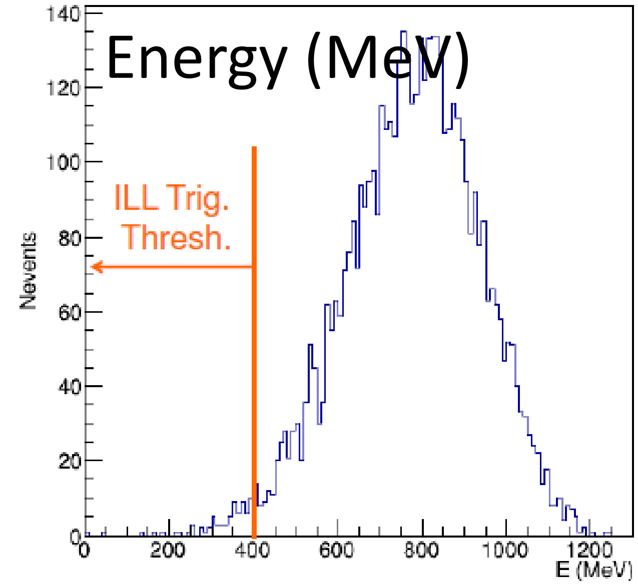


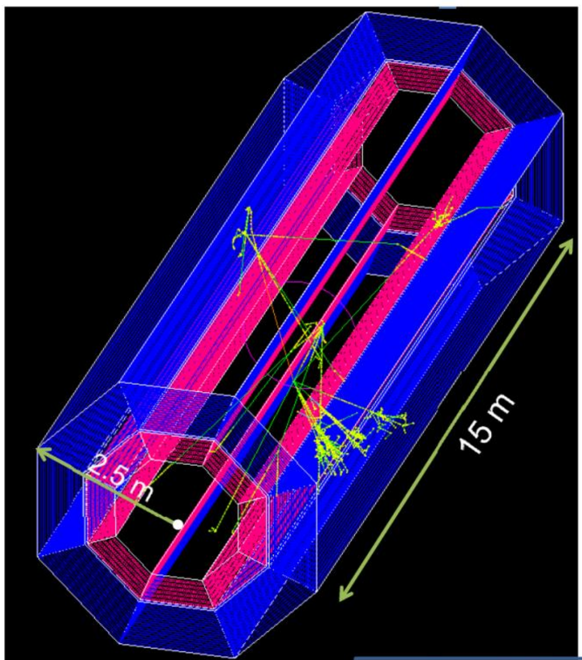
- Stochastic gamma backgrounds
- High energy n,p
- Beta-delayed n
- Cosmic rays - expected dominant

Selections on timing, energy, vertex.

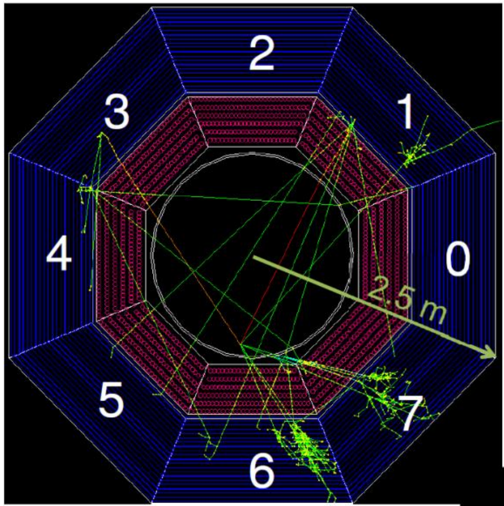
Observing $n \rightarrow \bar{n}$







$$\bar{n} + {}^{12}C \rightarrow {}^{11}C + \pi's$$



Capability of the experiment

Gain in $P_{n\bar{n}}$ □ 10^3 compared with ILL.

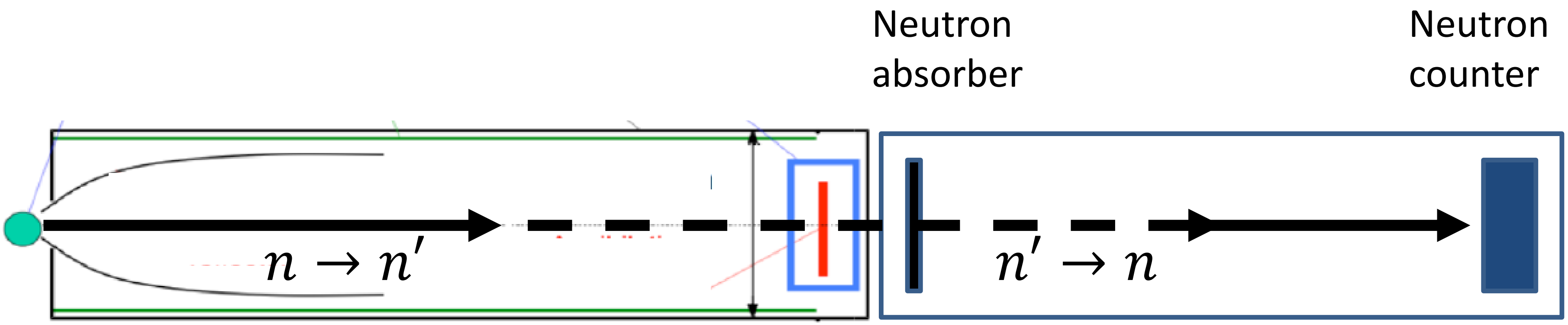
Factor	Gain wrt ILL
Brightness	≥ 1
Moderator temperature	≥ 1
Moderator area	2
Angular acceptance/neutron transmission	40
Length	5
Run time	3
Total	≥ 1000

Increase in sensitivity for $P_{n\bar{n}}$ □ 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.

Search for mirror neutrons



Classic regeneration experiment.

Magnetically controlled regions for transit.

Extend beyond previous searches for oscillation time and magnetic fields.

Proposed work

Stage 1

HIBEAM

Mid 2020's->late 2020's

$\rightarrow$ Sensitivity to $P\left(n \rightarrow \bar{n}\right)$ by up to factor 10

$\rightarrow$ Search for mirror neutrons (regeneration)

$\rightarrow$ Measurements of weak nucleon-nucleon interactions

Stage 2

Late 2020's + 5 years

Full experiment.

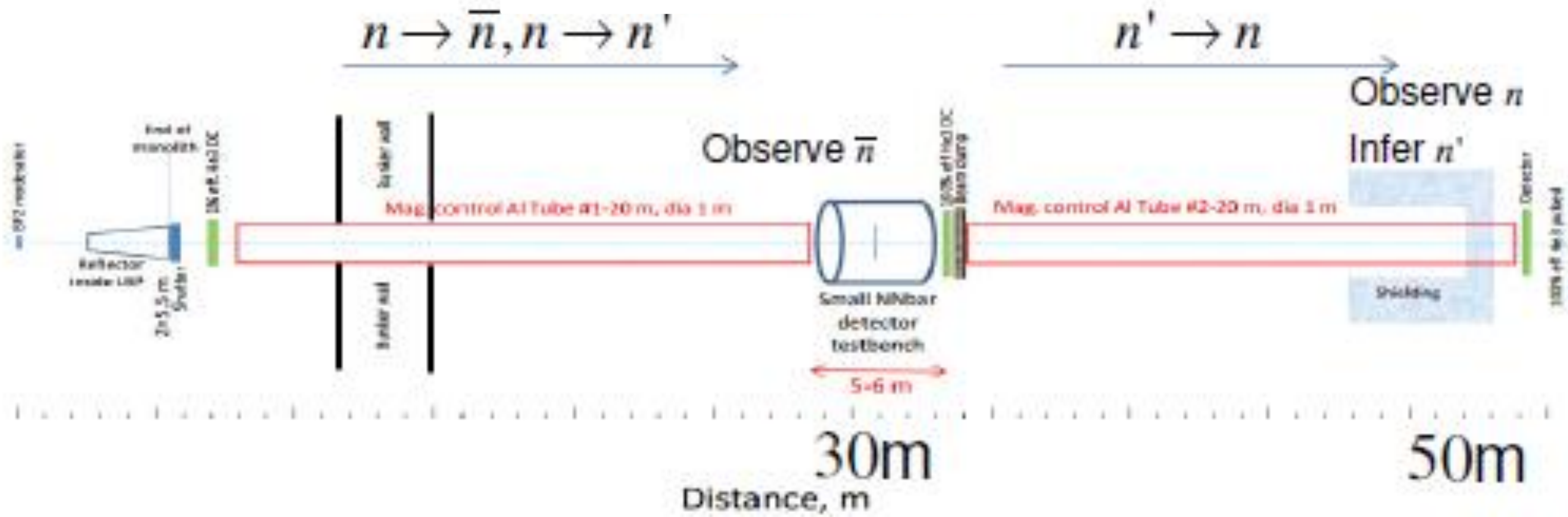
$\rightarrow$ Sensitivity to $P\left(n \rightarrow \bar{n}\right)$ by up to factor 10^3

$\rightarrow$ Further mirror neutron searches + measurements of weak nucleon-nucleon interactions.

Outline

1. The aims of the experiment ✓
2. The physics case ✓
3. The proposed program at the ESS ✓
4. Status

Stage 1



Reduced beamline - 30-50m

Includes "classic" regeneration experiment for mirror neutrons.

Prototyping and physics.

Collaboration

Six workshops (CERN, Lund, Gothenburg, NBI)

Collaboration formed – co-spokespersons G. Broojimans and D. Milstead
Lead scientist – Y. Kamishkov

Expression of Interest submitted to ESS.
Signatories from 26 institutes , 8 countries.

Preparations for a bid in 2018 to ESS.

ESS: First beam 2019
Fully operational 2025

More collaborators are welcome!

Particle Physics Strategy

European:

h) Experiments studying quark flavour physics, investigating dipole moments, searching for charged-lepton flavour violation and performing other precision measurements at lower energies, such as those with neutrons, muons and antiprotons, may give access to higher energy scales than direct particle production or put fundamental symmetries to the test. They can be based in national laboratories, with a moderate cost and smaller collaborations. *Experiments in Europe with unique reach should be supported, as well as participation in experiments in other regions of the world.*

US P5 report:

- With a mix of large, medium, and small projects, important physics results will be produced continuously throughout the twenty-year P5 timeframe. In our budget exercises, we maintained a small projects portfolio to preserve budgetary space for a set of projects whose costs individually are not large enough to come under direct P5 review but which are of great importance to the field. This is in addition to the aforementioned small neutrino experiments portfolio, which is intended to be integrated into a coherent overall neutrino program.

Consensus in the field is to pursue experiments with unique capabilities and physics reach.

Summary

- Searches for $n \to \bar{n}$, $n \to n'$ address open questions in modern physics.
  - An experiment at the ESS offers a new opportunity to extend sensitivity to neutron oscillation probability by several orders of magnitude and set a new limit on the stability of matter.
  - Collaboration formed and EOI
  - Provisional schedule

Other stuff

- n-p parity violation
- n-3He parity violation
- Exotic spin-dependent neutron interactions

- Require a neutron polarizer
- Use the weak force as a probe of the strong force.

Post-sphaleron baryogenesis

- Quark-lepton unification models
- Heavy scalar couples to SM fermions via $d=9$ operator
- Out of equilibrium at or below TeV scale
- BNV decay to six quark states -> baryogenesis