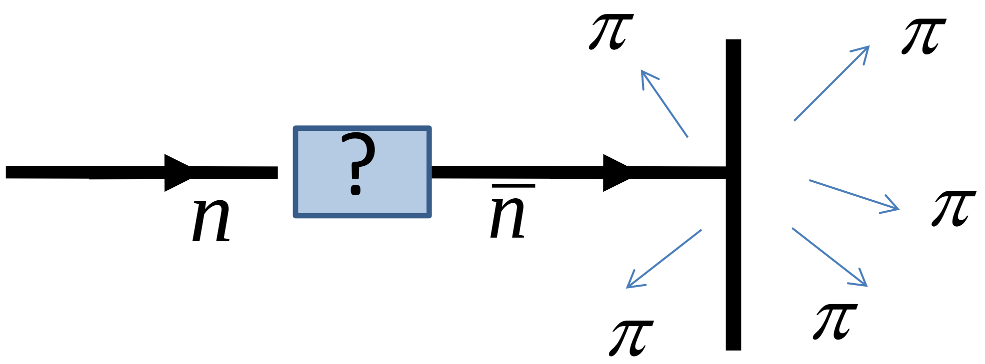
Hunting the missing baryon number violation at the ESS



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 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)

- Need to explore the possible selection rules:

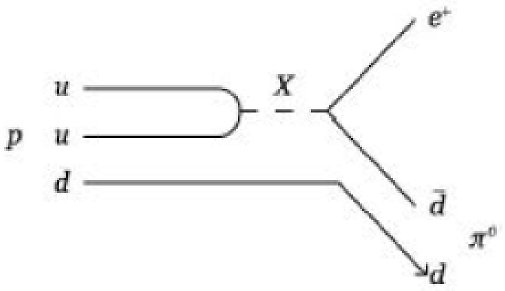
$$\boxed{\Delta B \neq 0\ ,\ \Delta L = 0,\ \Delta\left[B - L\right] \neq 0}$$

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

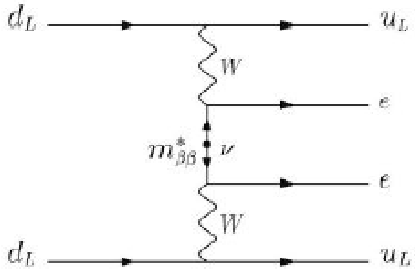
$$\Delta L \neq 0\ ,\ \ \Delta B \neq 0,\ \Delta\left[B - L\right] = 0$$

.....

Complementary BNV, LNV observables



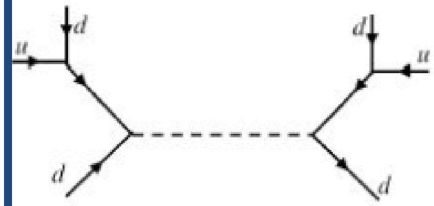
$$p \to e^+ + \pi^0$$
$$\Delta B \neq 0, \Delta L \neq 0$$



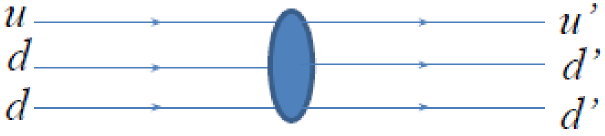
$$0\nu 2\beta$$
$$\Delta B = 0, \Delta L \neq 0$$

Symbiosis

Neutron oscillation



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



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

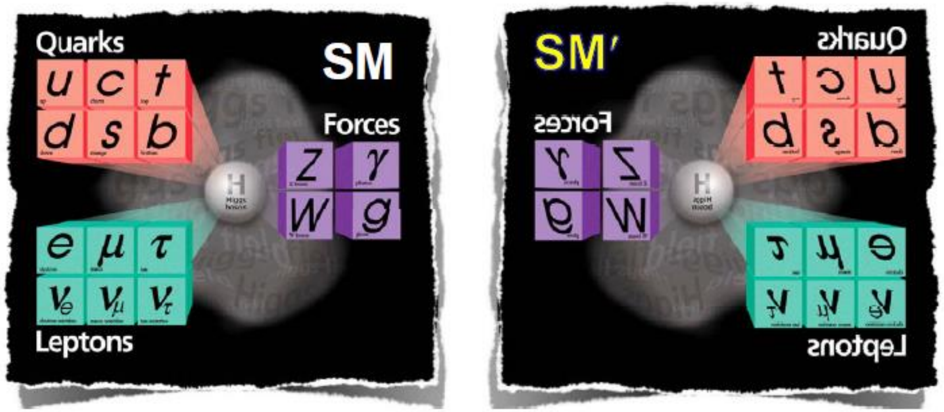
Mirror neutrons

"Hidden/mirror" sector

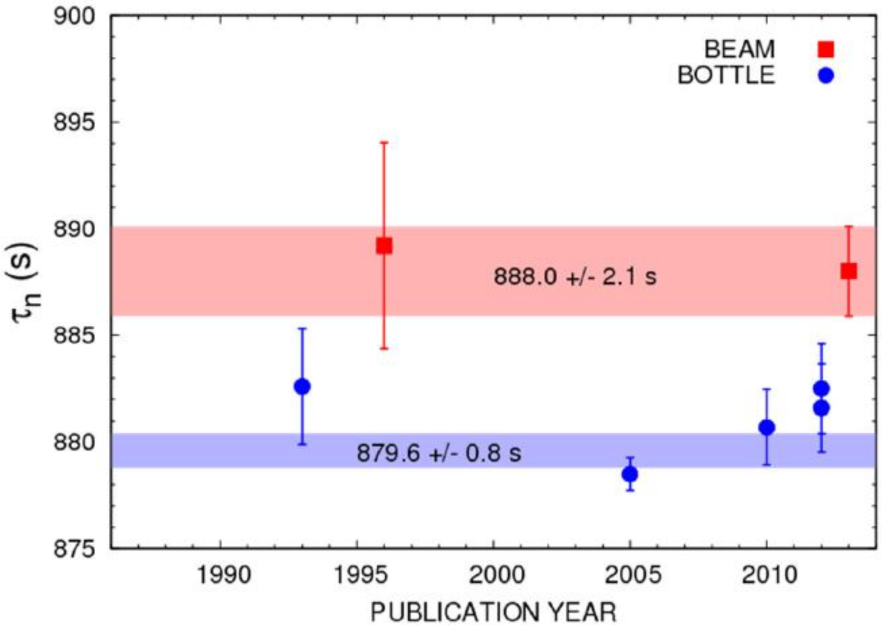
Restores parity symmetry.

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.



Neutron-antineutron oscillations

- R-parity violating supersymmetry, minimal flavour violation SUSY
- Unification models: $M \sim 10^{15}$ GeV
- Left-right symmetric models ($n\bar{n}$ and $0\nu 2\beta$)
- 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.

Operator analysis

Six quark operators $\mathcal{O}_i$:

$$(u_R d_R d_R)^2 \equiv \epsilon_{abc} u^a_{R\dot\alpha} d^{\dot\alpha b}_R d^c_{R\dot\gamma}\ \epsilon_{def} u^d_{R\dot\beta} d^{\dot\beta e}_R d^{\dot\gamma f}_R$$

$$(u_R d_R d_L)^2 \equiv \epsilon_{abc} u^a_{R\dot\alpha} d^{\dot\alpha b}_R d^{\gamma c}_L\ \epsilon_{def} u^d_{R\dot\beta} d^{\dot\beta e}_R d^f_{L\gamma}$$

$$(u_L d_L d_R)^2 \equiv \epsilon_{abc} u^{\alpha a}_L d^b_{L\alpha} d^c_{R\dot\gamma}\ \epsilon_{def} u^{\beta d}_L d^e_{L\beta} d^{\dot\gamma f}_R$$

$$(u_R d_R s_R)^2 \equiv \epsilon_{abc} u^a_{R\dot\alpha} d^{\dot\alpha b}_R s^c_{R\dot\gamma}\ \epsilon_{def} u^d_{R\dot\beta} d^{\dot\beta e}_R s^{\dot\gamma f}_R\,.$$

$n \to \bar{n},\ NN \to \pi\pi$

$NN \to KK$

Eg $n \to \bar{n}$:

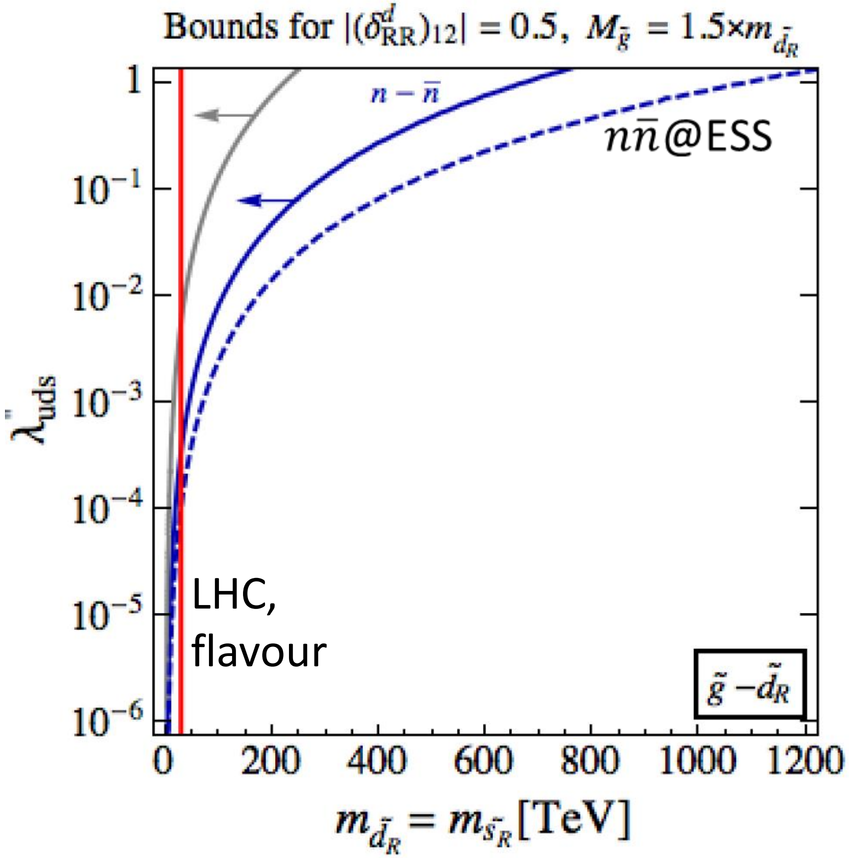
$$\langle \bar{n} | \mathcal{H}_{eff} | n \rangle = \frac{1}{M_X^5} \sum_i \kappa_i \langle \bar{n} | \mathcal{O}_i | n \rangle$$

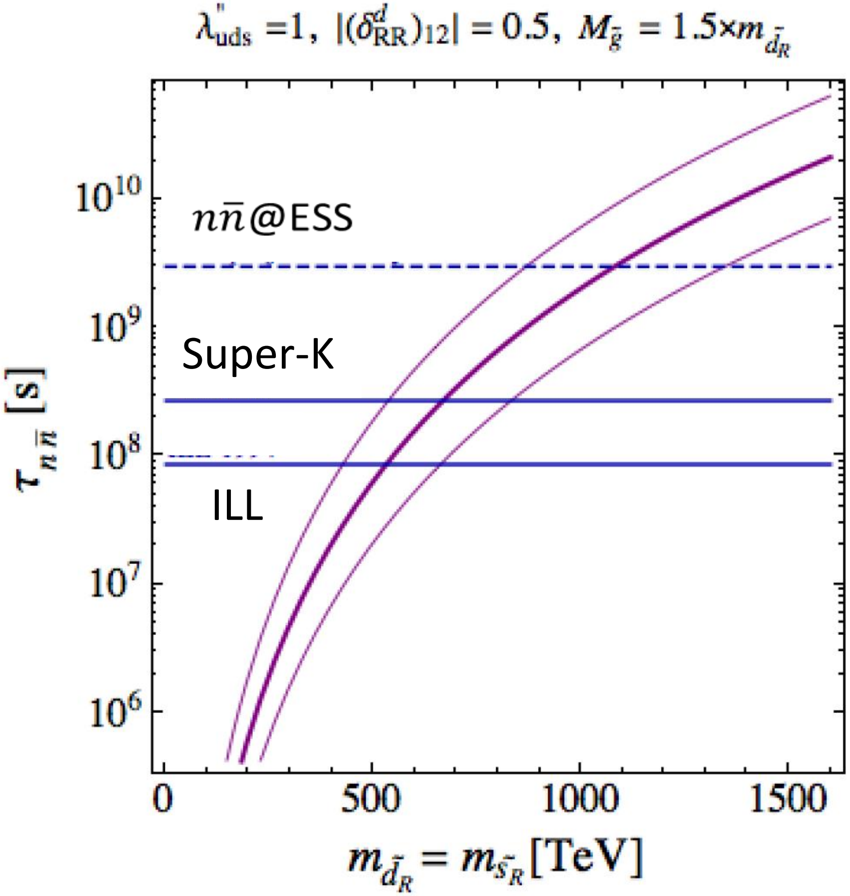
Short distance (RPV SUSY): κ_i

Long distance Hadronic ME: $\langle \bar{n} | \mathcal{O}_i | n \rangle \sim \Lambda_{QCD}^6$

Oscillation time $\tau = \dfrac{1}{\langle \bar{n} | \mathcal{H}_{eff} | n \rangle} \sim \dfrac{M_X^5}{\kappa \Lambda_{QCD}^6}$

Beyond the TeV scale





Constraints vanish for >> TeV masses

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

: pushes into the PeV scale

: Reach beyond the LHC

An experimentalist’s view (1)

Hypothesis: baryon number is weakly violated. How do we look for it ?

Need processes in which only BNV takes place.

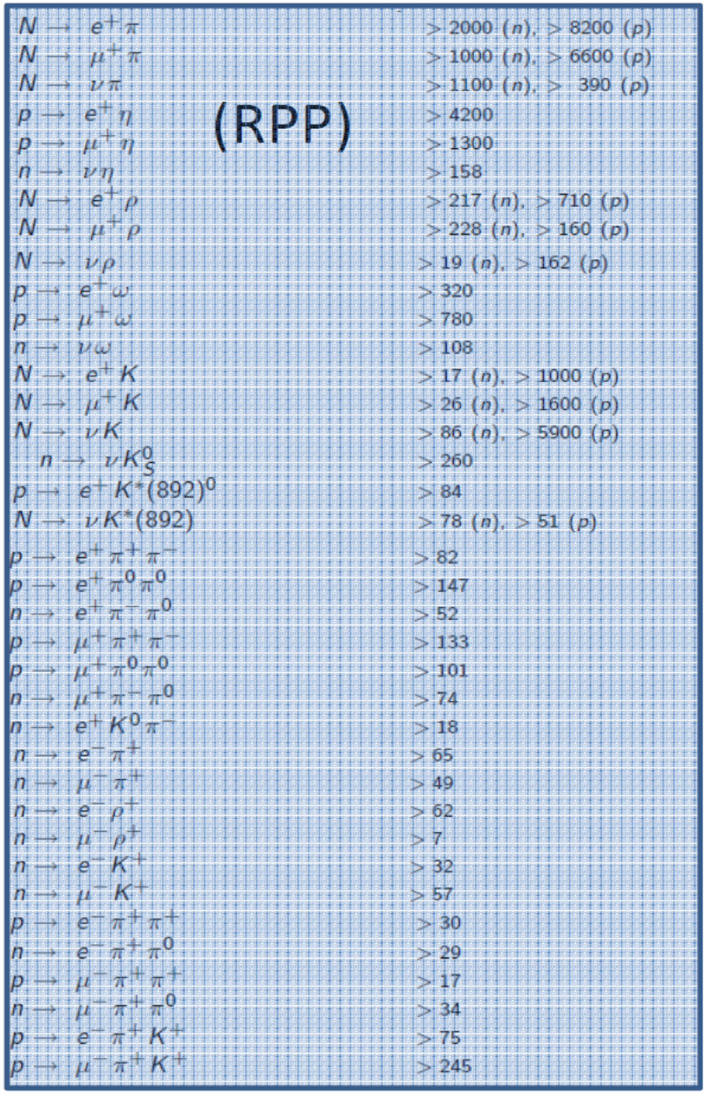
Single nucleon decay searches, eg, $p \to \pi^0 + e^+$?
$\Rightarrow \; |\Delta B| = 1$, $|\Delta L| = 1$!

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

$|\Delta B| \neq 0$, $\Delta L = 0$ observables restricted by Nature.

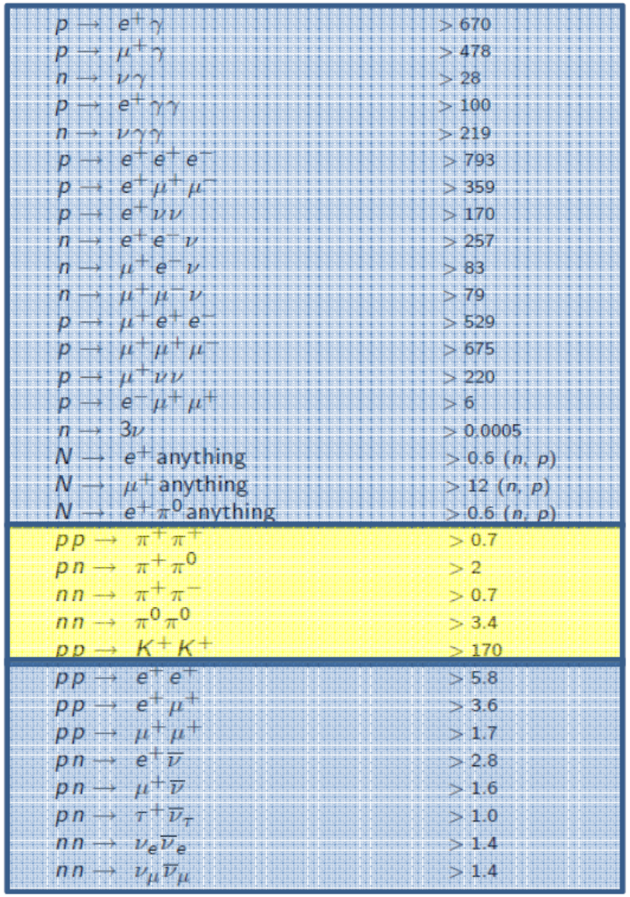
$n \to \bar{n}, n'$ and dinucleon decay searches sensitive to BNV-only.
Free $n \to \bar{n}, n'$ searches $\Rightarrow$ cleanest experimental and theoretical approach.

An experimentalist’s view (2)



(RPP)

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)
$n \rightarrow \nu K^0_S$	> 260
$p \rightarrow e^+K^*(892)^0$	> 84
$N \rightarrow \nu K^*(892)$	> 78 (n), > 51 (p)
$p \rightarrow e^+\pi^+\pi^-$	> 82
$p \rightarrow e^+\pi^0\pi^0$	> 147
$n \rightarrow e^+\pi^-\pi^0$	> 52
$p \rightarrow \mu^+\pi^+\pi^-$	> 133
$p \rightarrow \mu^+\pi^0\pi^0$	> 101
$n \rightarrow \mu^+\pi^-\pi^0$	> 74
$n \rightarrow e^+K^0\pi^-$	> 18
$n \rightarrow e^-\pi^+$	> 65
$n \rightarrow \mu^-\pi^+$	> 49
$n \rightarrow e^-\rho^+$	> 62
$n \rightarrow \mu^-\rho^+$	> 7
$n \rightarrow e^-K^+$	> 32
$n \rightarrow \mu^-K^+$	> 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



Decay mode	Partial mean life ($\times 10^{30}$ yrs)
$p \rightarrow e^+\gamma$	> 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
$p \rightarrow e^+\nu\nu$	> 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
$p \rightarrow \mu^+\nu\nu$	> 220
$p \rightarrow e^-\mu^+\mu^+$	> 6
$n \rightarrow 3\nu$	> 0.0005
$N \rightarrow e^+$ anything	> 0.6 (n, p)
$N \rightarrow \mu^+$ anything	> 12 (n, p)
$N \rightarrow e^+\pi^0$ anything	> 0.6 (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
$pn \rightarrow e^+\overline{\nu}$	> 2.8
$pn \rightarrow \mu^+\overline{\nu}$	> 1.6
$pn \rightarrow \tau^+\overline{\nu}_\tau$	> 1.0
$nn \rightarrow \nu_e\overline{\nu}_e$	> 1.4
$nn \rightarrow \nu_\mu\overline{\nu}_\mu$	> 1.4

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

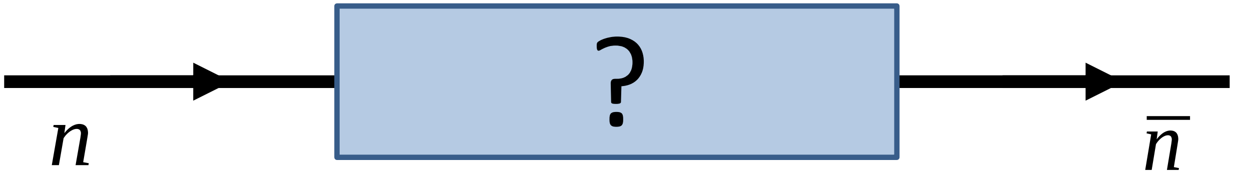
$$\Delta B \neq 0, \Delta L = 0$$

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

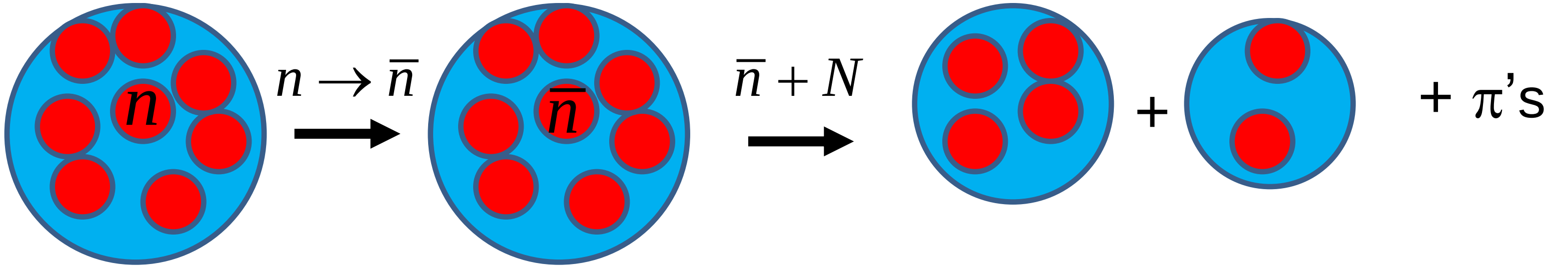
$$P_{n\rightarrow\bar{n}} = \left(\frac{\delta m}{\Delta E}\right)^2 \sin^2\left(\Delta E \times t\right) \quad ; \; \Delta E = \; E_n - E_{\bar{n}}$$

Two interesting cases:

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

Searching with bound neutrons

Nuclear disintegration after neutron oscillation



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

$\Delta E \sim 100$ MeV .

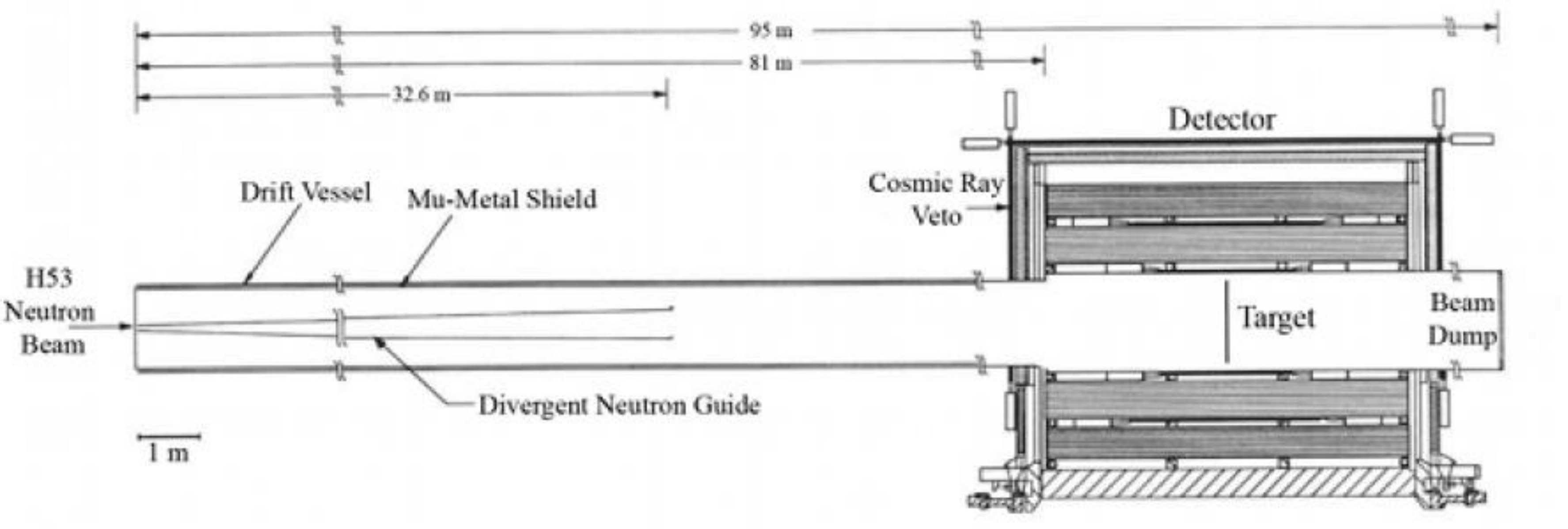
$\Rightarrow$ Suppression: $\left(\frac{\delta m}{\Delta E}\right)^2 < 10^{-60}$

Best current limits (SuperKamiokande) $\Rightarrow$ $\tau_{free} > 2.5\times10^8$ 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

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

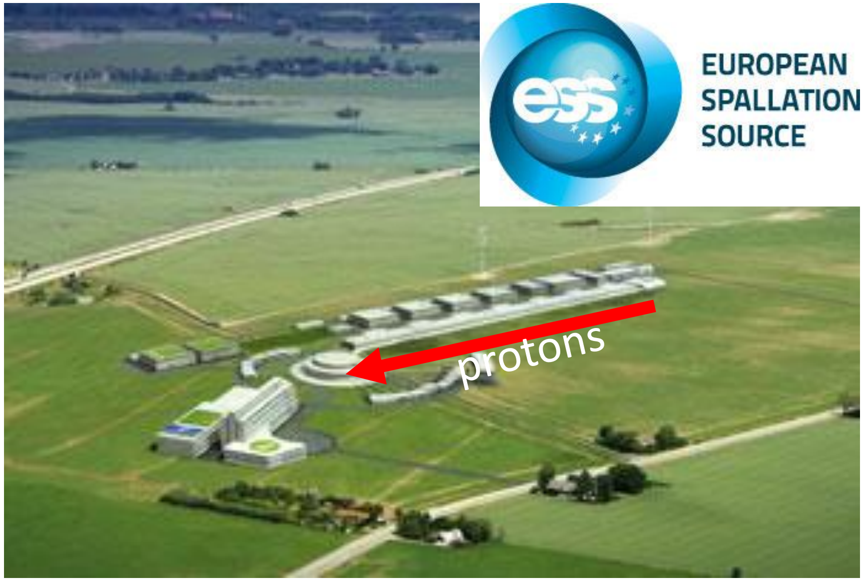
- Why neutron oscillations ? ✓
- How to look for neutron oscillations ✓
- Nnbar and HIBEAM at the ESS

The European Spallation Source

High intensity spallation neutron source

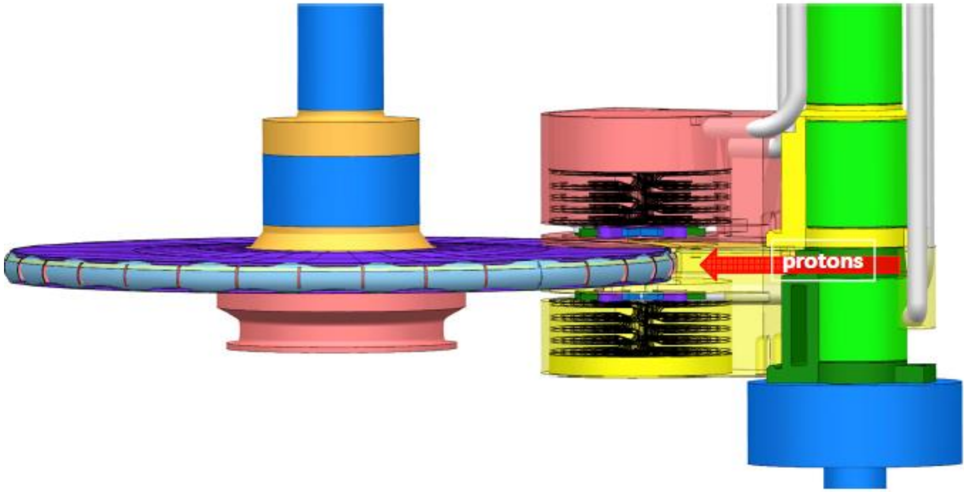
Multidisplinary research centre with 17 European nations participating.

Lund, Sweden.
Start operations in 2023/2024.

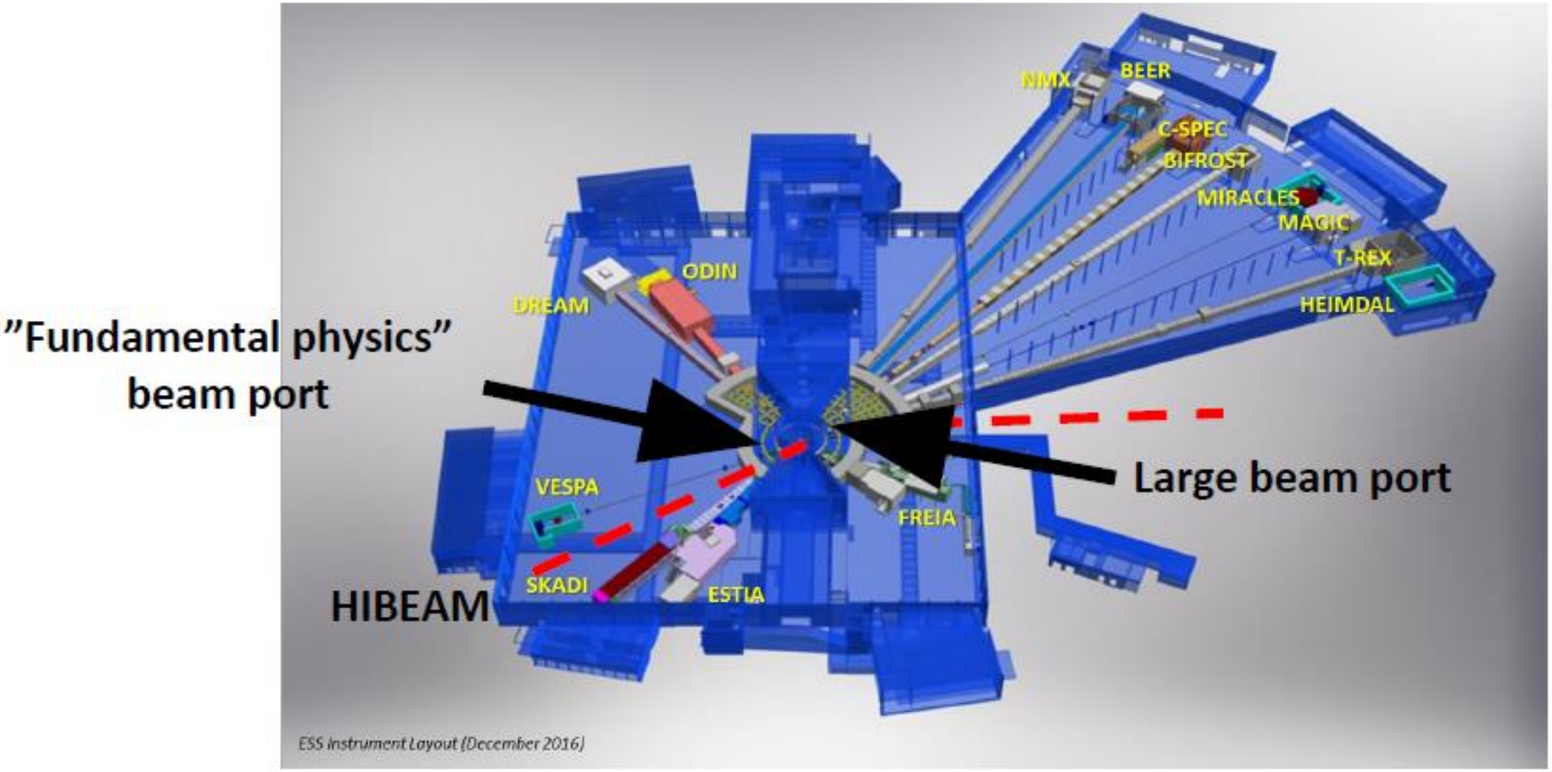


2 GeV protons (3ms long pulse, 14 Hz) hit rotating tungsten target.

Cold neutrons after interaction with moderators.



HIBEAM



ESS instrument Layout (December 2016)

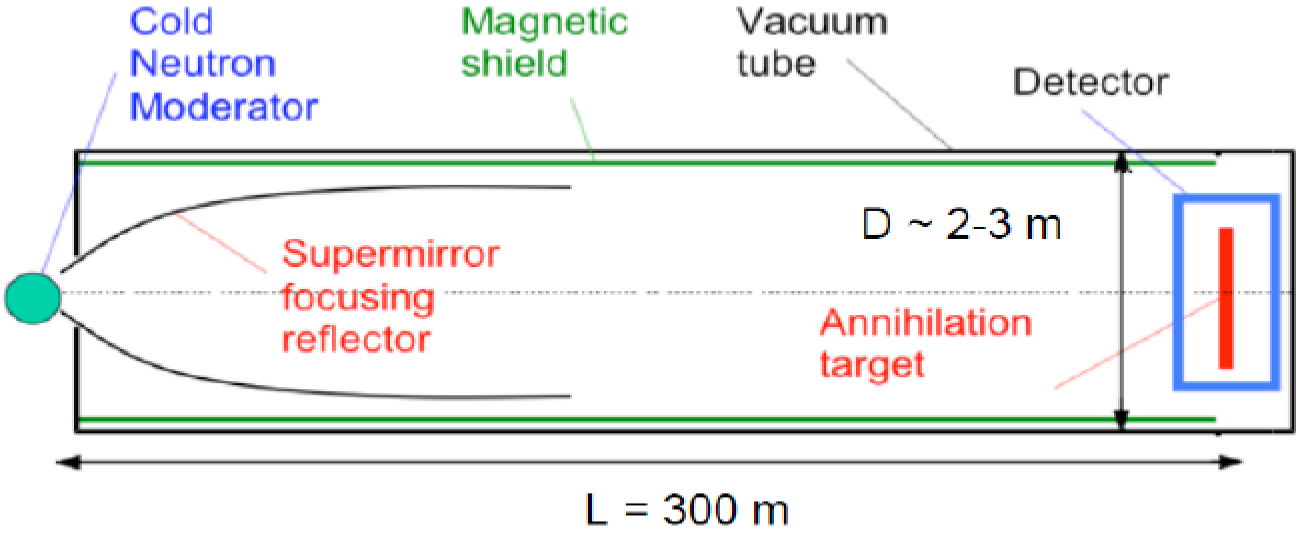
~ 22 instruments/experiments with capability for more.

Plan for staged experiment:

(1) HIBEAM (high intensity baryon extraction and measurement) at Fundamental Physics Beam Port

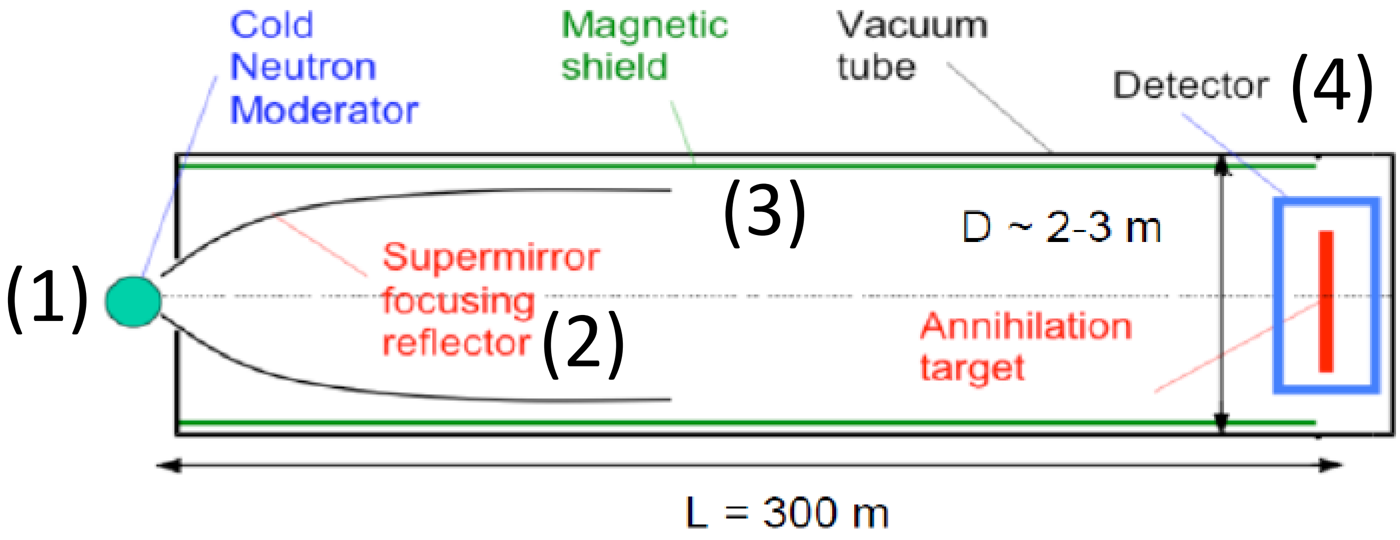
(2) NNbar at the Large Beam Port.

Overview of the Experiment

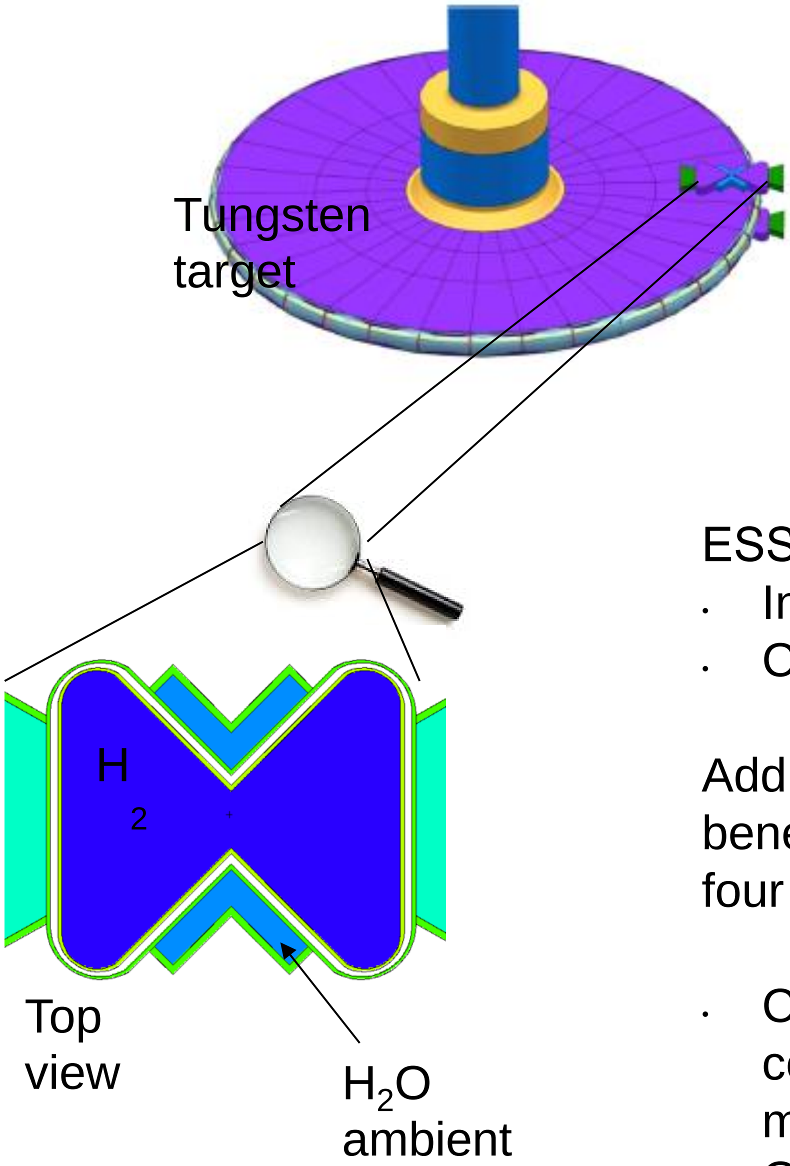


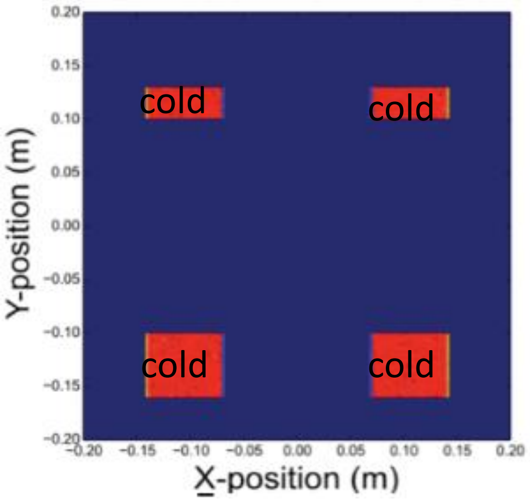
$$\boxed{\text{Sensitivity} = (\text{free neutron flux at target}) \times P(n \to \bar{n}) \propto N_n t^2}$$

- 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.


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

Neutronics (1)



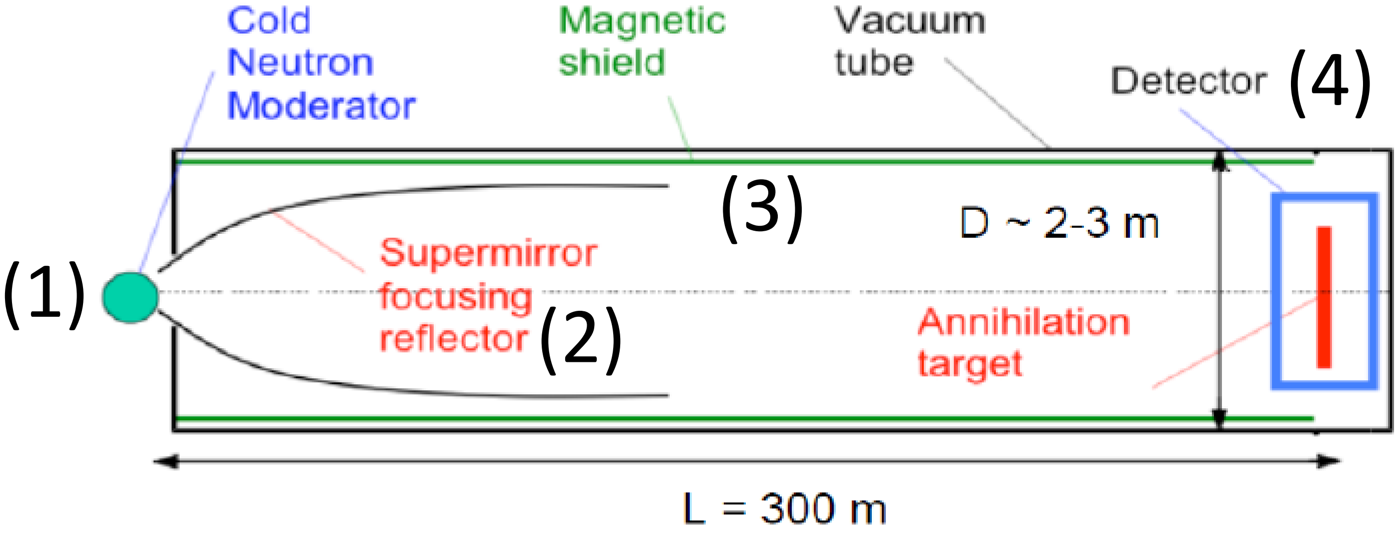


ESS moderators will be of "butterfly" design

- Increase cold yield
- Convenient beam extraction

Additional challenge for nnbar which could benefit from extracting neutrons from all four visible cold surfaces

- Conventional point-to-point focusing of a cold neutron beam using ellipsoidal mirrors inefficient.
- Ongoing studies on neutron optics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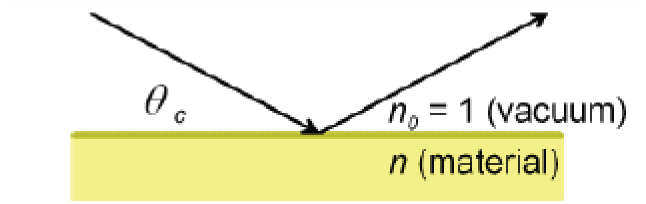
(4)
(3)
D ~ 2-3 m
Supermirror
focusing
reflector
(2)
(1)
Annihilation
target
L = 300 m

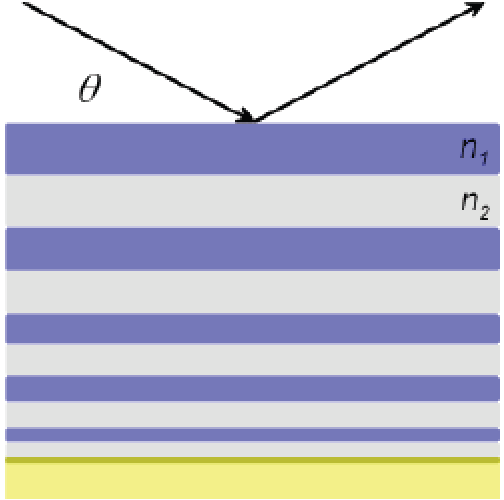
Neutron supermirror

Smooth surface

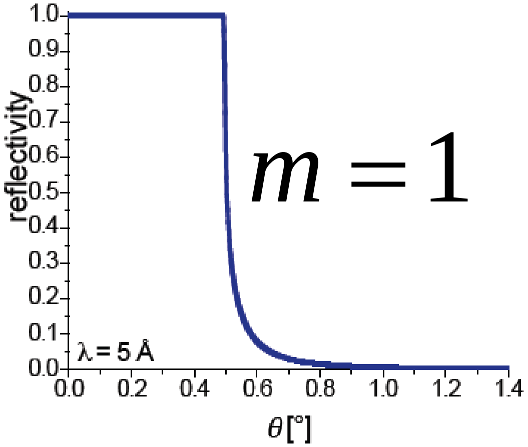


θ_c=Critical angle for total internal reflection

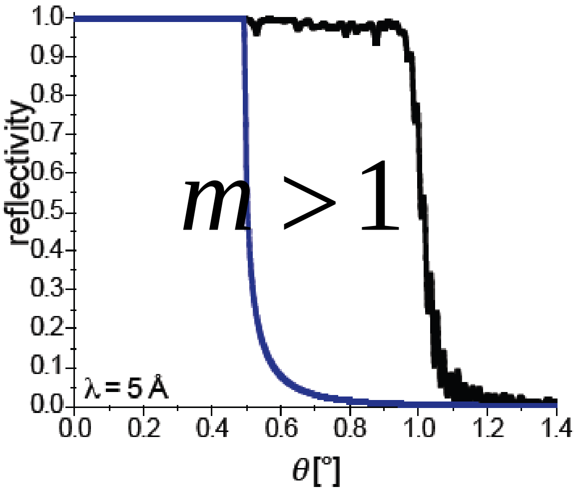
Supermirror



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



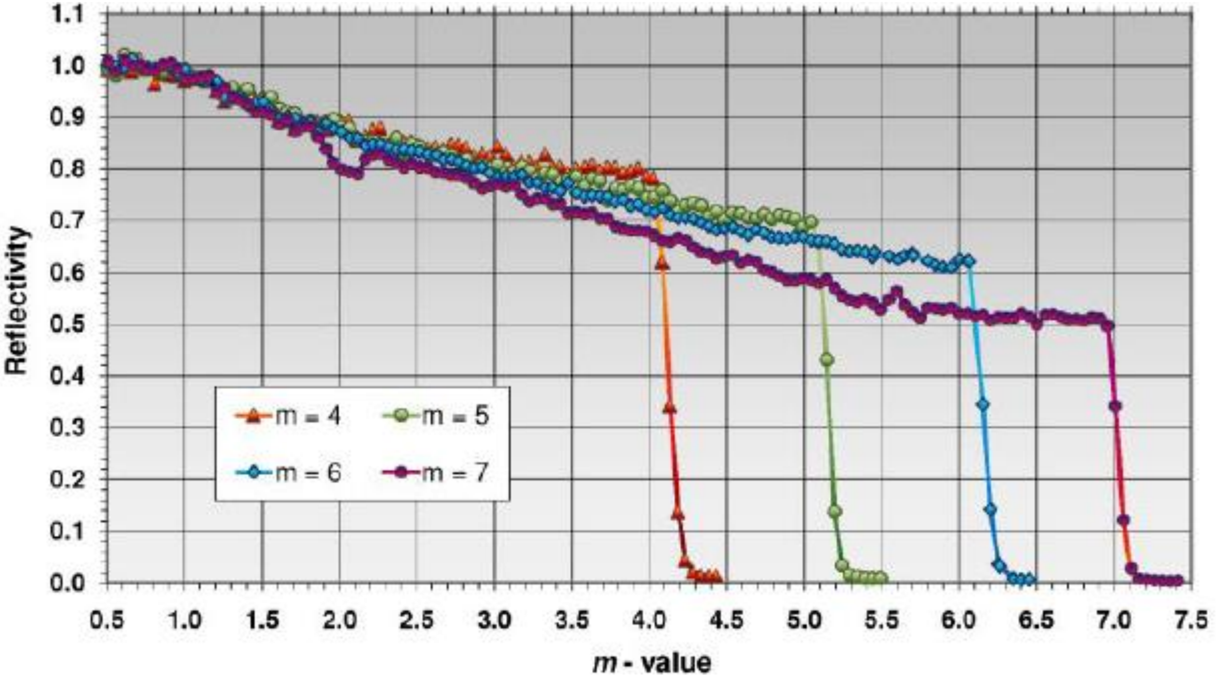
$$m = 1$$



$$m > 1$$

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

Commercial supermirrors



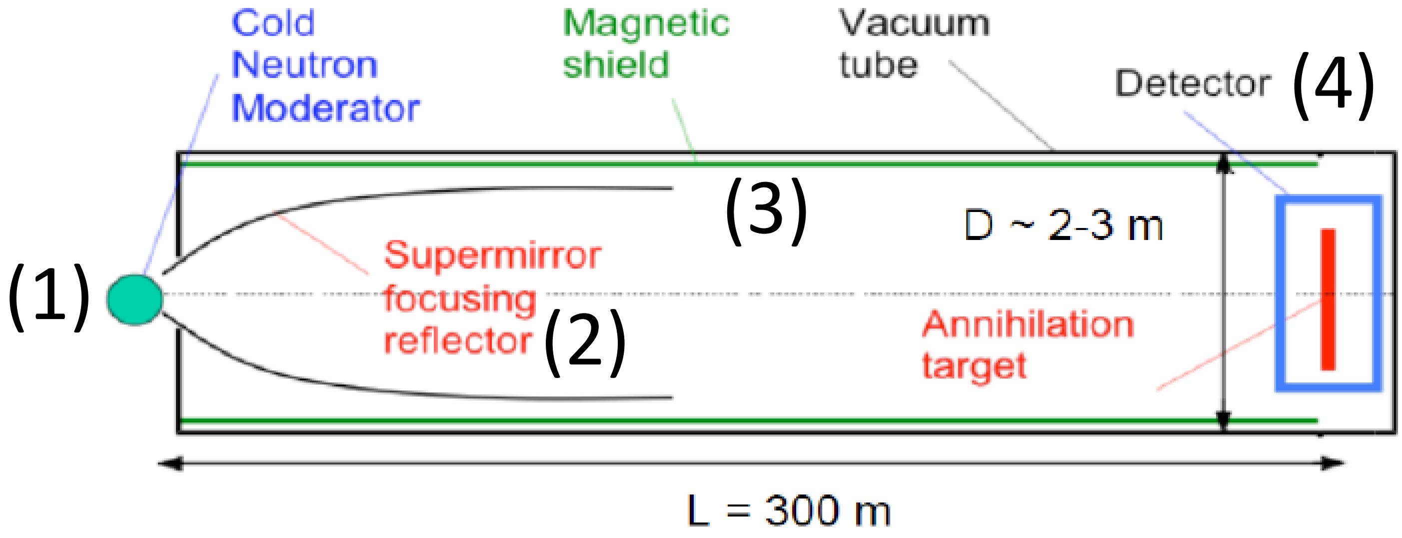
Commercial supermirrors with $m \sim 7$

Acceptance for straight guide $\propto m^2$

ILL experiment used $m \sim 1$ neutron optics.

Increase from use of focusing reflector and optimised mirror arrays.

Crucial contribution to increase of sensitivity wrt ILL.


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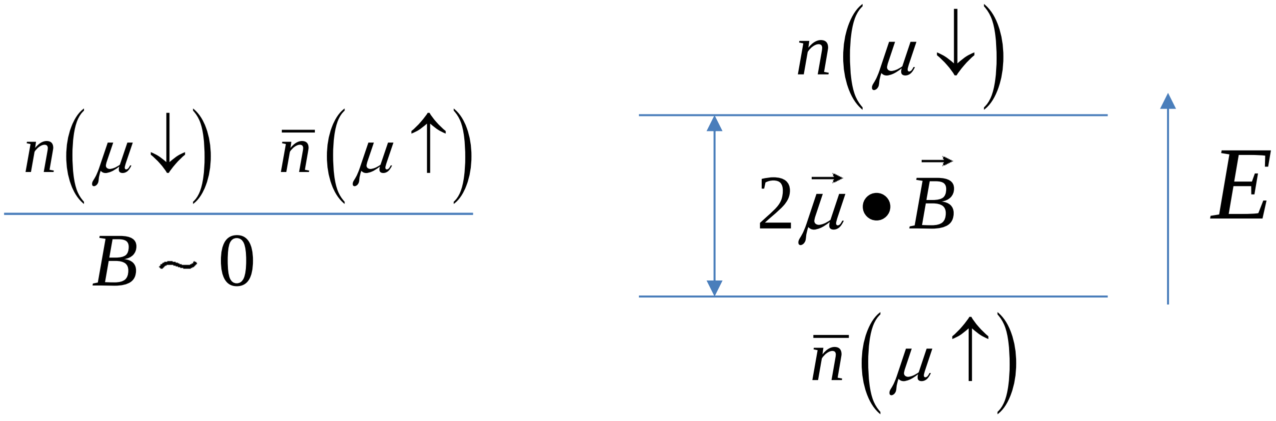
Detector
(4)
(3)
D ~ 2-3 m
(1)
Supermirror
focusing
reflector
(2)
Annihilation
target
L = 300 m

The need for magnetic shielding



$n(\mu\downarrow)$ $\bar{n}(\mu\uparrow)$

$B \sim 0$

$n(\mu\downarrow)$

$2\vec{\mu}\bullet\vec{B}$

E

$\bar{n}(\mu\uparrow)$

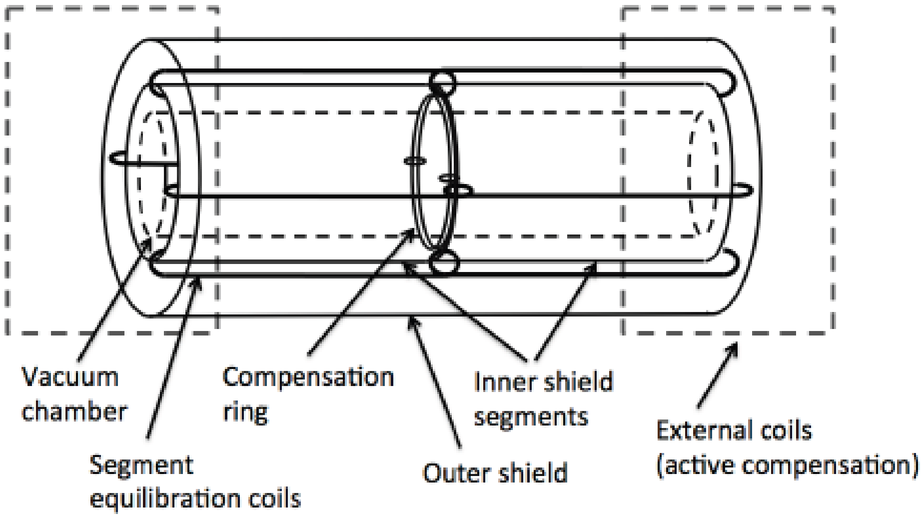
Degeneracy of $n, \bar{n}$ broken in B-field due to dipole interactions: $\Delta E = 2\vec{\mu}\bullet\vec{B}$

Flight time ≤ 1s

For quasi-free condition $\Delta E \times t \ll 1$

$\Rightarrow B \leq 5$nT and vacuum $\leq 10^{-5}$ Pa.

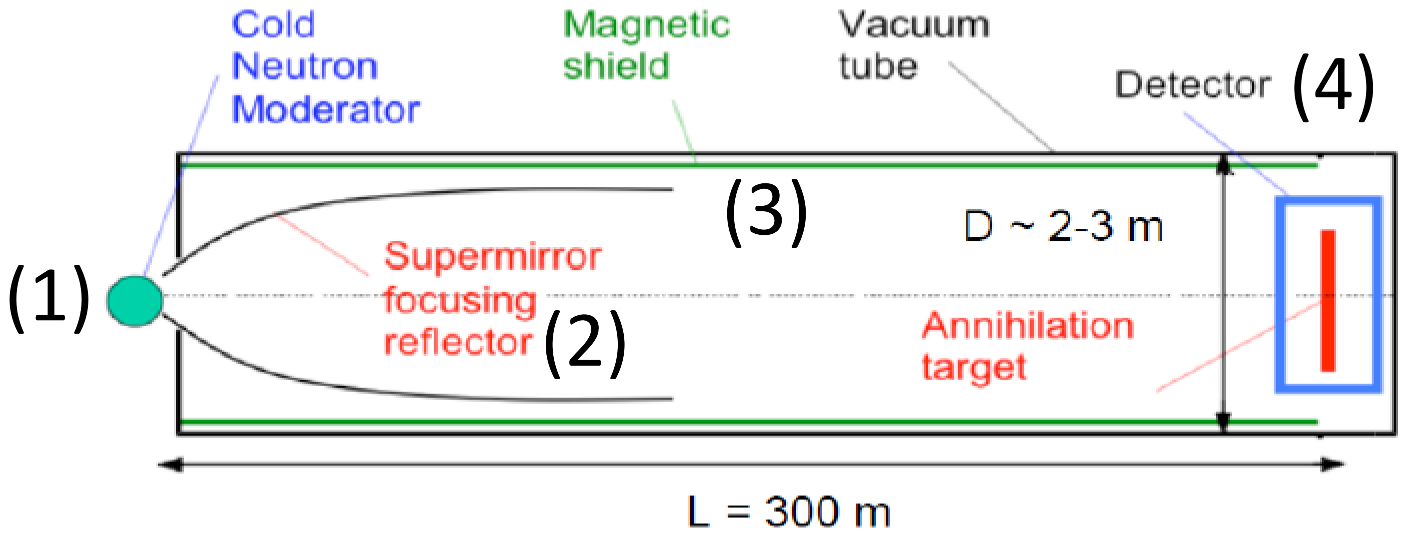
Shielding



Magnetic shielding for flight volume

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

Overview of the Experiment



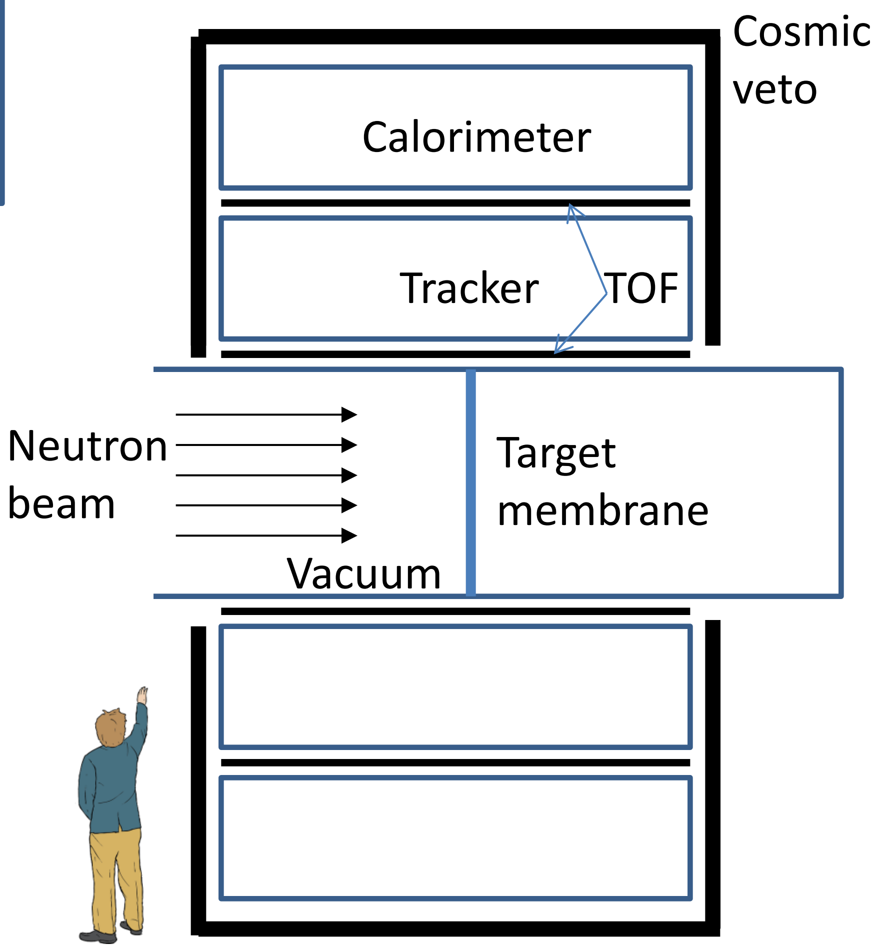
Detector

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



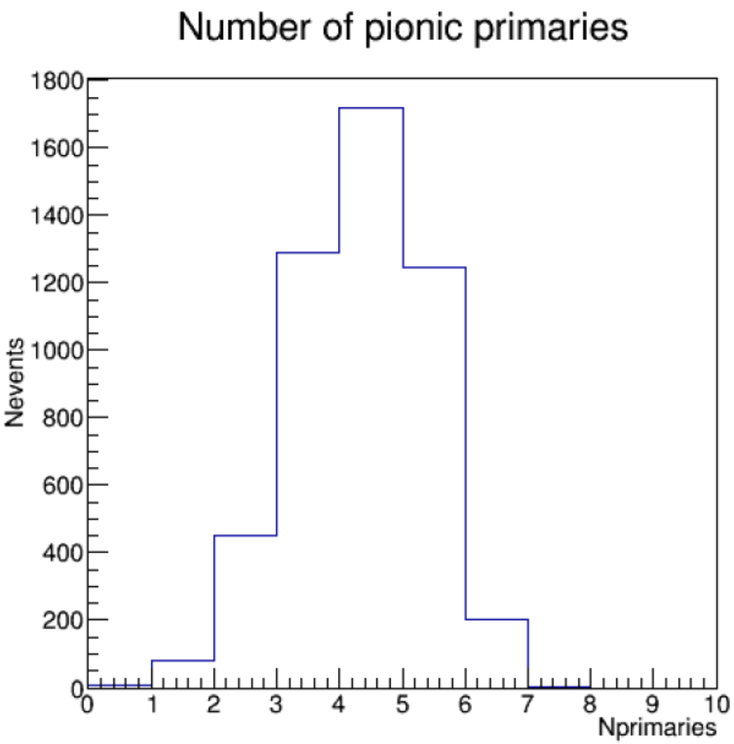
GENIE: NNBar Final State Primaries

Preliminary

Final state list prepared by R. W. Pattie

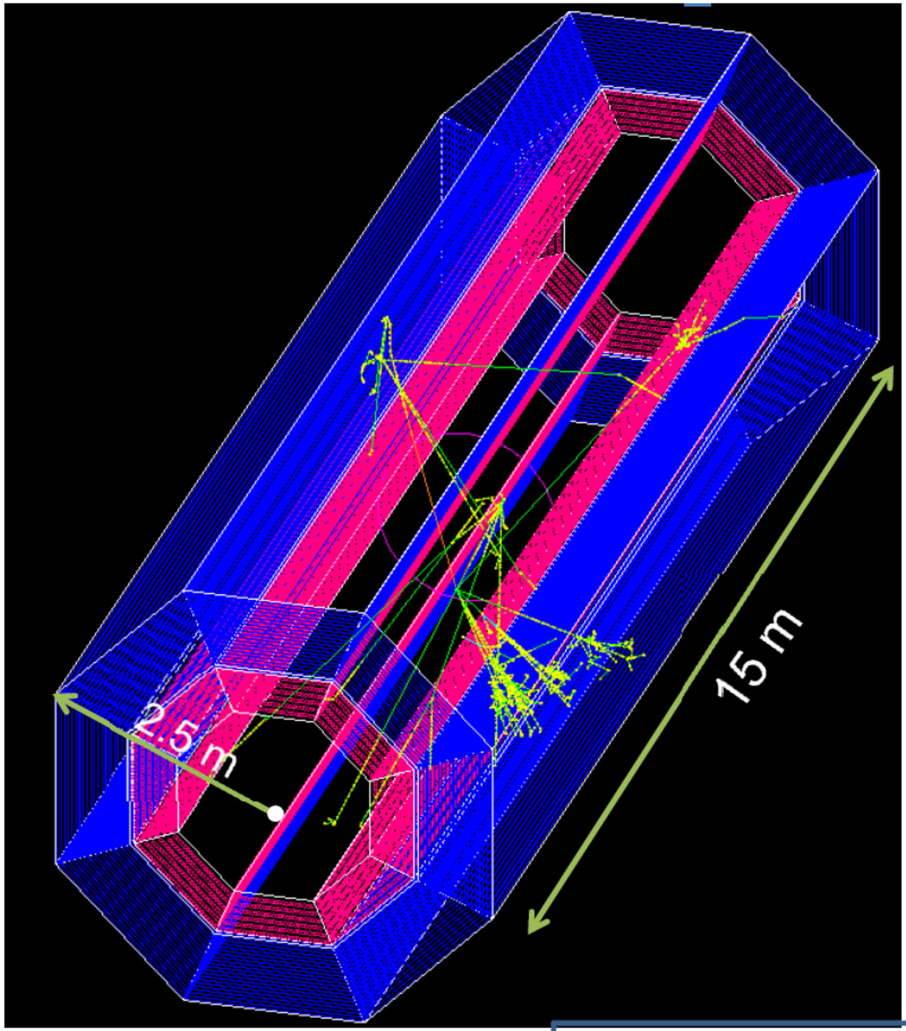
GENIE-2.0.0: intranculear propagation based on INTRANUKE

C.Andreopoulos et al., The GENIE Neutrino Monte Carlo Generator, Nucl.Instrum.Meth.A614:87-104,2010.

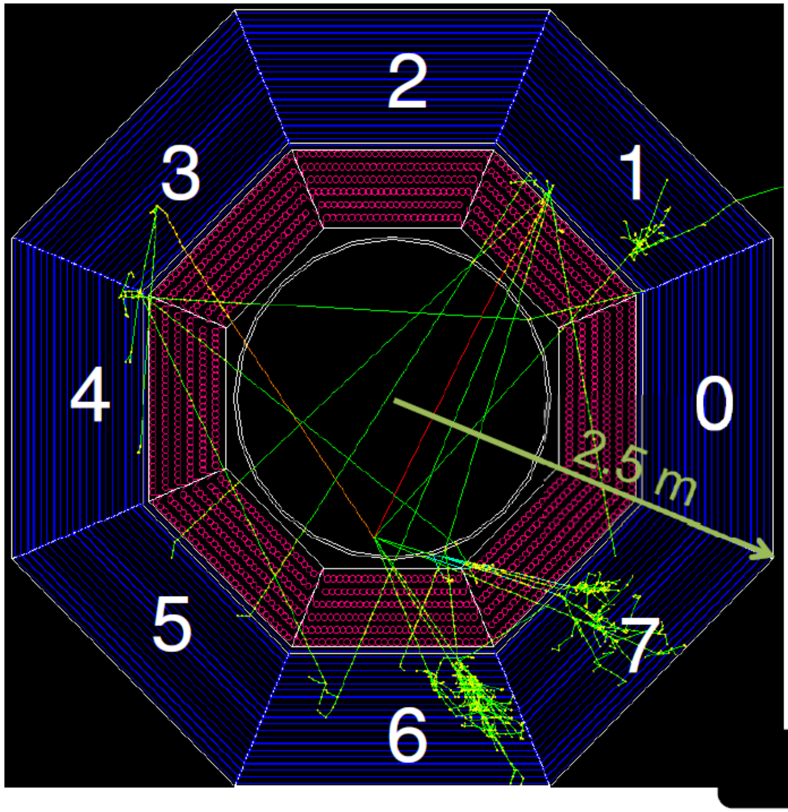


Final State Pionic Mode	Nevents	% Total
$\pi^+\pi^-2\pi^0$	530	10.60%
$2\pi^+\pi^-\pi^0$	486	9.72%
$\pi^+\pi^-\pi^0$	417	8.34%
$2\pi^+\pi^-2\pi^0$	409	8.18%
$\pi^+\pi^-3\pi^0$	329	6.58%
$2\pi^+2\pi^-\pi^0$	315	6.30%
$\pi^+2\pi^0$	290	5.80%
$\pi^+3\pi^0$	219	4.38%
$\pi^+\pi^-\omega$	145	2.90%
$\pi^+\pi^0$	137	2.74%
$\pi^+2\pi^-\pi^0$	132	2.64%
$2\pi^+2\pi^-$	124	2.48%

Annihilation event



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



Capability of the experiment

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

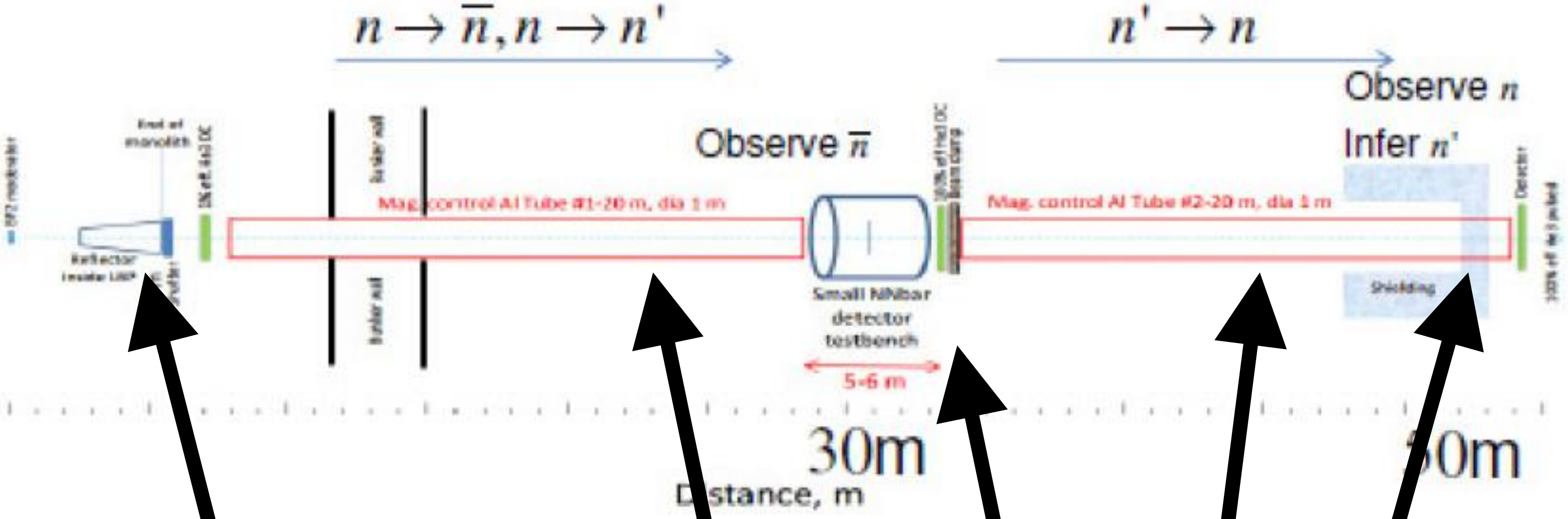
Factor	Gain wrt ILL
Brightness	≥ 1
Moderator temperature	≥ 1
Moderator area	2
Angular acceptance/neutron transmission	40
Length	5
Run time	3
Total	≥ 1000

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.

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

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

NNBAR experiment

Late 2020’s + 5 years

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

HIBEAM/nnbar and ESS

HIBEAM/nnbar

Six workshops (CERN, Lund, Gothenburg, Copenhagen)

Expression of Interest 2015.

26 institutes, 8 countries.

Co-spokespersons : G. Broojimans, D. Milstead

Lead scientist: Y. Kamyshkov

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.

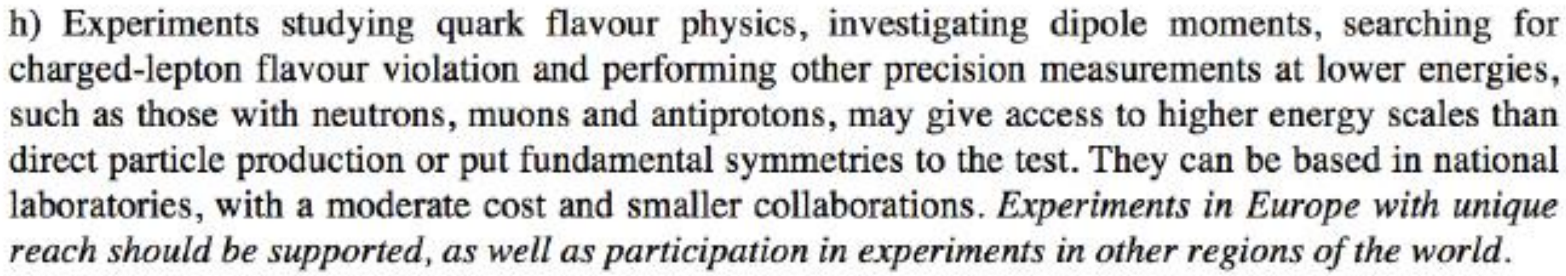
Successful application → 10-14 Meuros.

Neutron-Anti-Neutron Oscillations at ESS

Lund, Feb 18-19, 2015

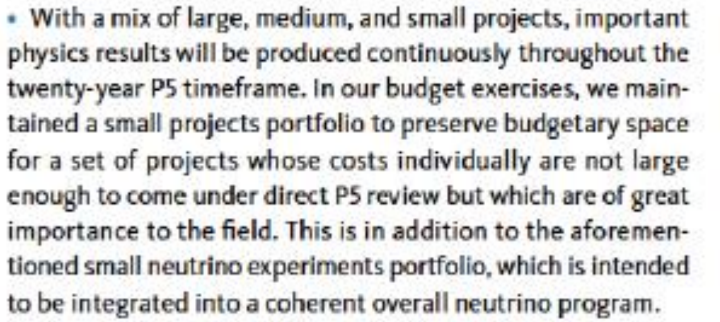
Particle Physics Strategy

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.*

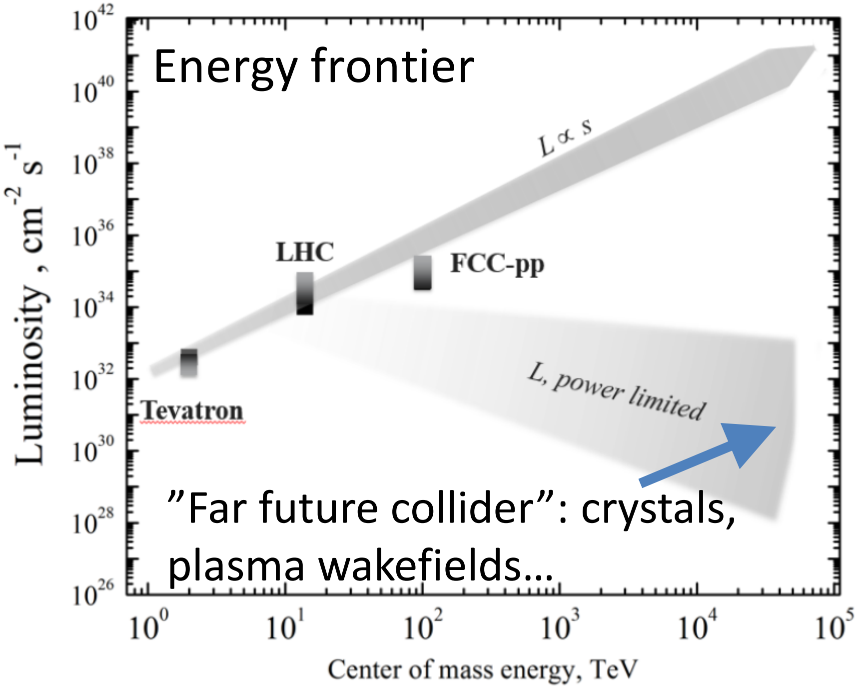
US P5 report:



- 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.

We live in interesting times



Energy frontier

”Far future collider”: crystals, plasma wakefields…

Future discoveries or walking a few km in a desert ?

For the first time in 50 years, going to higher collision energies no longer offers a clear path to discoveries or fundamental insights.

Need a complementary set of collider +non-collider experiments with unique physics potentials and reach of energy scale.

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

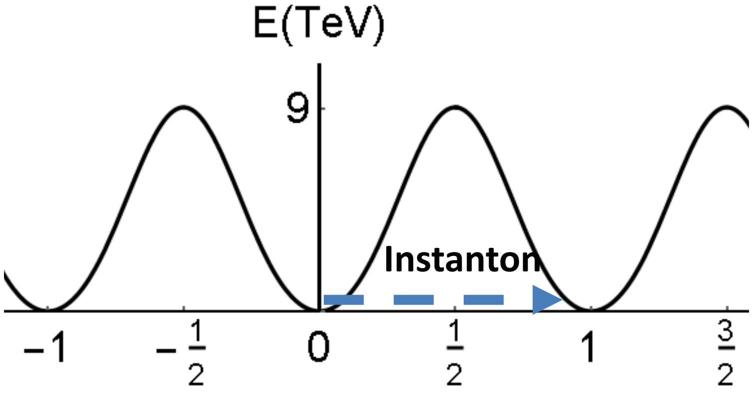
- *Follows the European Particle Strategy of supporting a set of experiments with complementary and unique physics reach.*

EW instantons in the Standard Model

Bosonic sector of EW theory

Infinite no. of field configurations (vacua)

Vacua distinguished by fermion energy levels.



Instantons:

Tunnelling between vacua minima $\equiv$

Fluctuation of background W field.

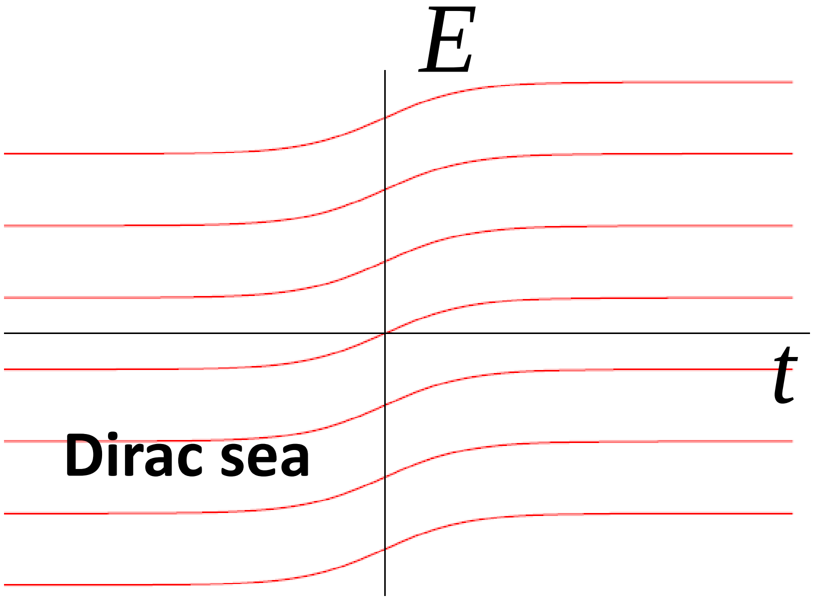
Energy level raises above (or falls below)

the surface of the Dirac sea.

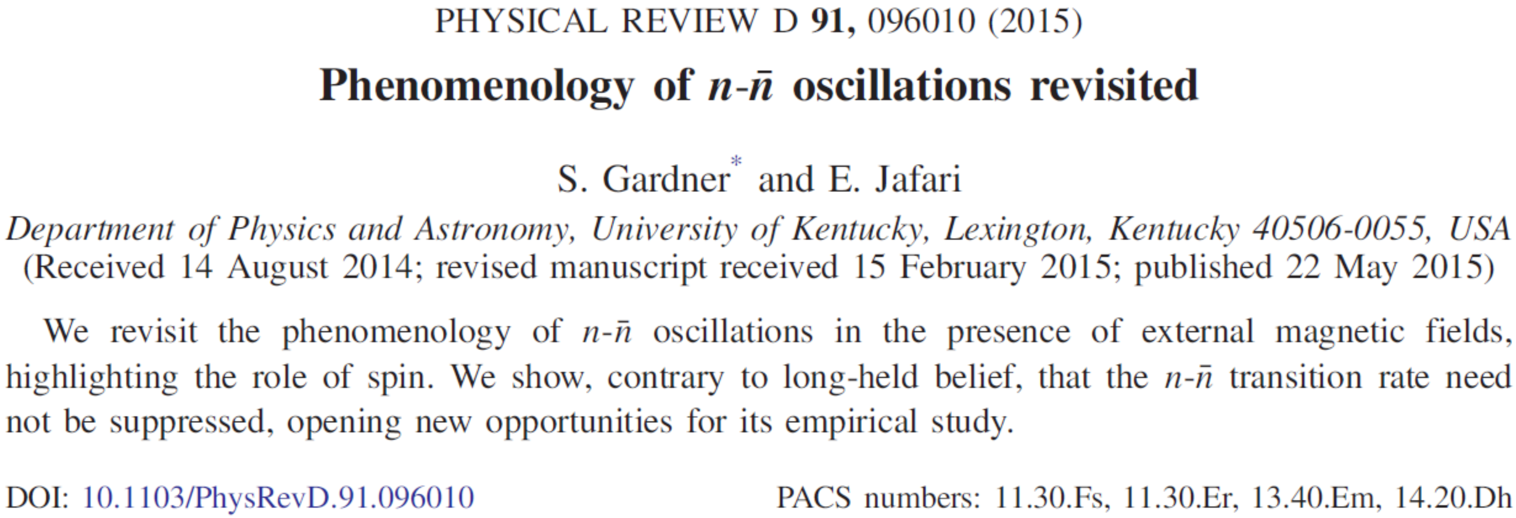
$\Rightarrow$ No. leptons and quarks changes

$\Rightarrow$ $\Delta L = \Delta B \neq 0, \ \Delta(B-L)=0, \ \Delta(B+L) \neq 0$

Exponentially suppressed: $\exp\left(-\frac{2\pi}{g_W}\right)$



Maybe shielding isn’t needed



PHYSICAL REVIEW D **91,** 096010 (2015)

Phenomenology of *n*-$\bar{n}$ oscillations revisited

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(Received 14 August 2014; revised manuscript received 15 February 2015; published 22 May 2015)

We revisit the phenomenology of n-$\bar{n}$ oscillations in the presence of external magnetic fields, highlighting the role of spin. We show, contrary to long-held belief, that the n-$\bar{n}$ transition rate need not be suppressed, opening new opportunities for its empirical study.

DOI: 10.1103/PhysRevD.91.096010 PACS numbers: 11.30.Fs, 11.30.Er, 13.40.Em, 14.20.Dh

Interesting discussion in the literature.