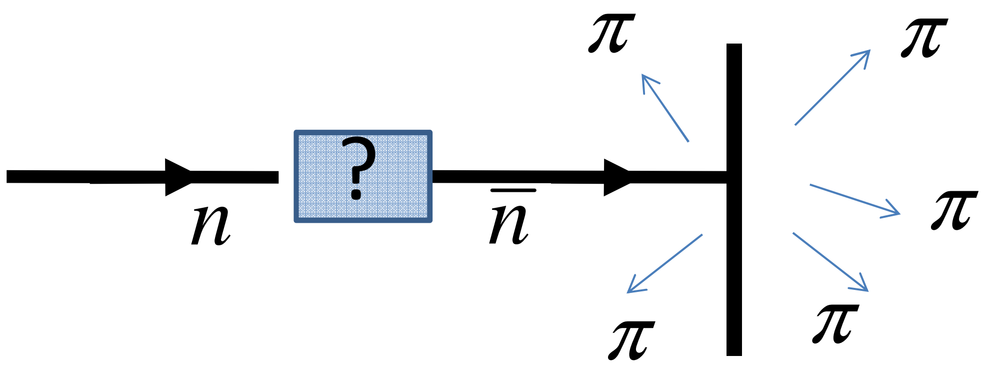
A search for free $n \rightarrow \overline{n}$ oscillations at the ESS



D. Milstead
Stockholm University

Why baryon number violation ?

Why baryon number violation ?

- Baryon number is not a ”sacred” quantum number
  - Approximate conservation of BN in SM
    - ”Accidental” global symmetry at perturbative level
      - Depends on specific matter content of the SM
    - BNV in SM by non-perturbative processes
      - Sphalerons
      - B-L conserved in SM, not B,L separately.
  - Generic BNV in BSM theories, eg, SUSY.
  - BNV a Sakharov condition for baryogenesis

Why $n \rightarrow \bar{n}$?

$$n \rightarrow \overline{n}$$

- Theory
  - Baryogenesis via $\cancel{BNV}$ (Sakharov condition)
  - SM extensions from TeV mass scales scale-upwards
  - Complementarity with open questions in neutrino physics

- Experiment
  - One of the few means of looking for pure BNV
  - Stringent limit on stability of matter

Neutron oscillations – models

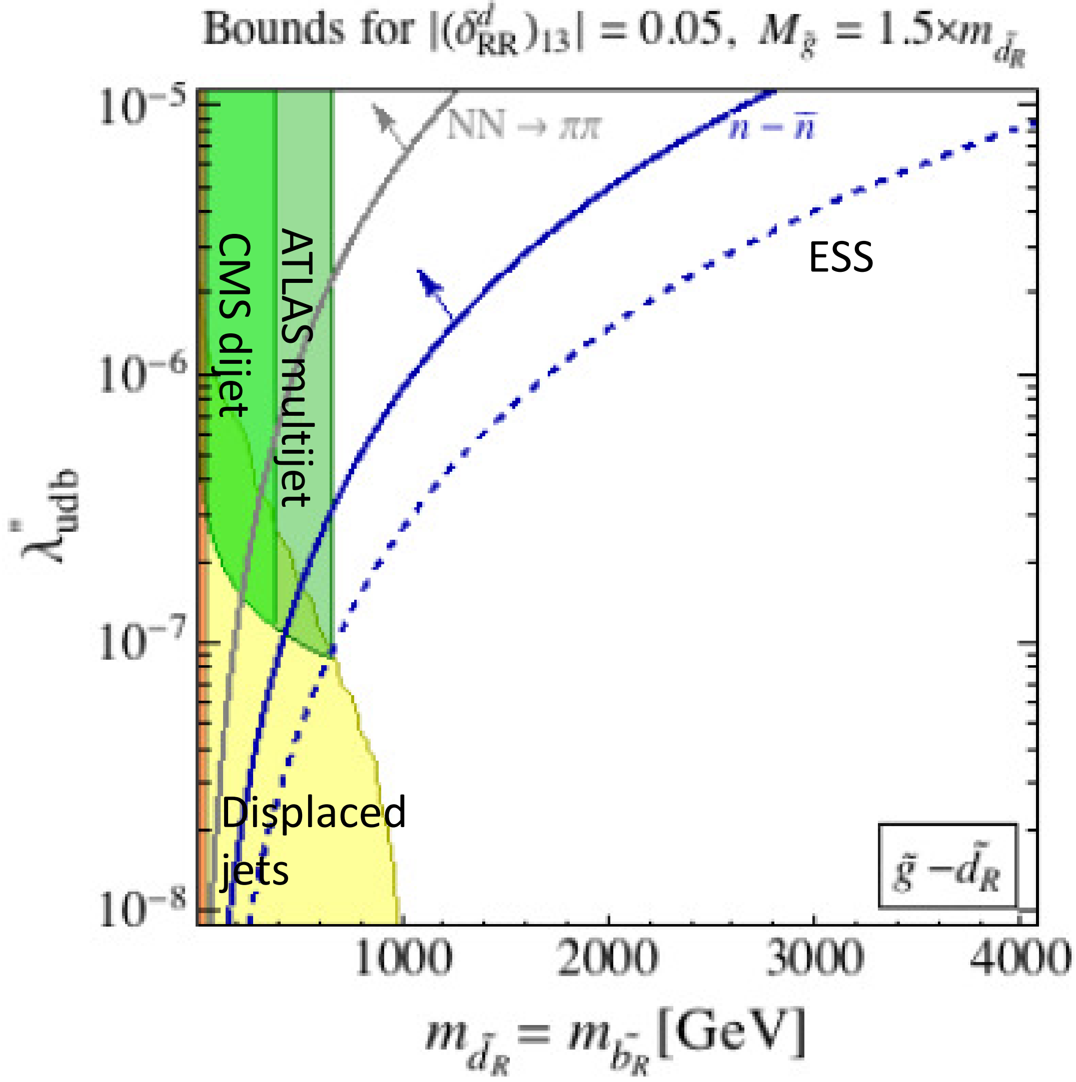
- Back-of-envelope dimensional reasoning:

6 q 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 models: $M \sim 10^{15}$ 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.

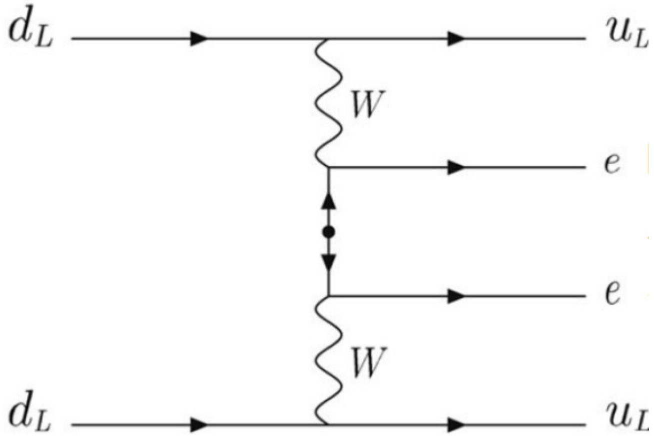
Extend sensitivity in RPV-SUSY



Arxiv:1602.04821 (hep-ph)

RPV-SUSY – TeV-scale sensitivity

Neutrino physics $\Leftrightarrow$ neutron oscillations

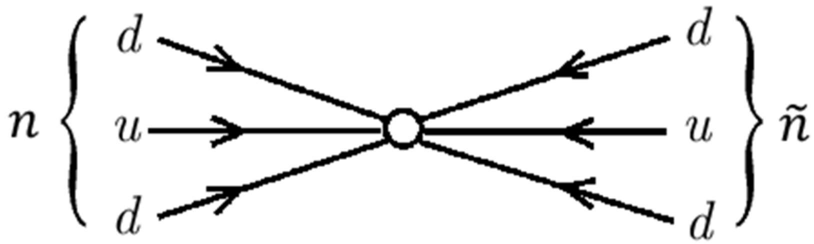


Neutrinoless 2β-decay

Eg seesaw mechanism for light ν

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

$\Delta|(B-L)| = 2$



$n \to \bar{n}$

Eg Unification models

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

$\Delta|(B-L)| = 2$

Neutrinoless 2β-decay $\Leftrightarrow$ $n \to \bar{n}$ linked under B - L violation.

Eg Left-right symmetric models.

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 and nnbar@ESS

(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)
$pp \to \pi^+ \pi^+$	> 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 $\Delta B \neq 0, \Delta L = 0$

Limits on τ_{life} from all searches

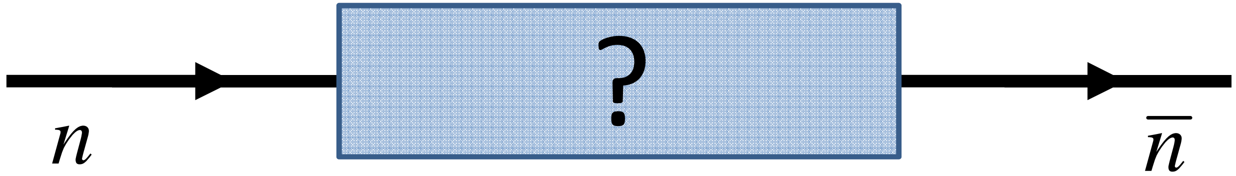
$\sim 10^{30} - 10^{34}$ yrs

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

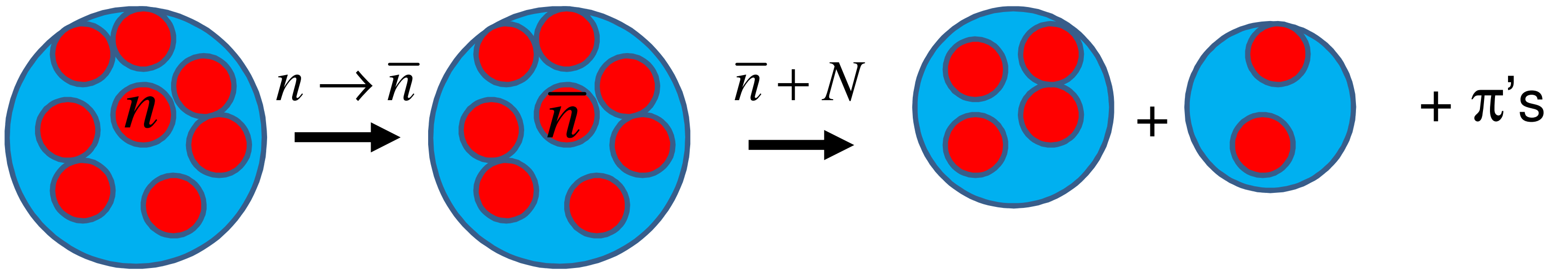
$$P_{n\rightarrow\bar{n}} = \left(\frac{\delta m}{\Delta E}\right)^2 \sin^2\left(\Delta E \times t\right) \quad ; \; \Delta E = \; E_n - E_{\bar{n}}$$

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



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

$\Delta E \sim 100$ MeV .

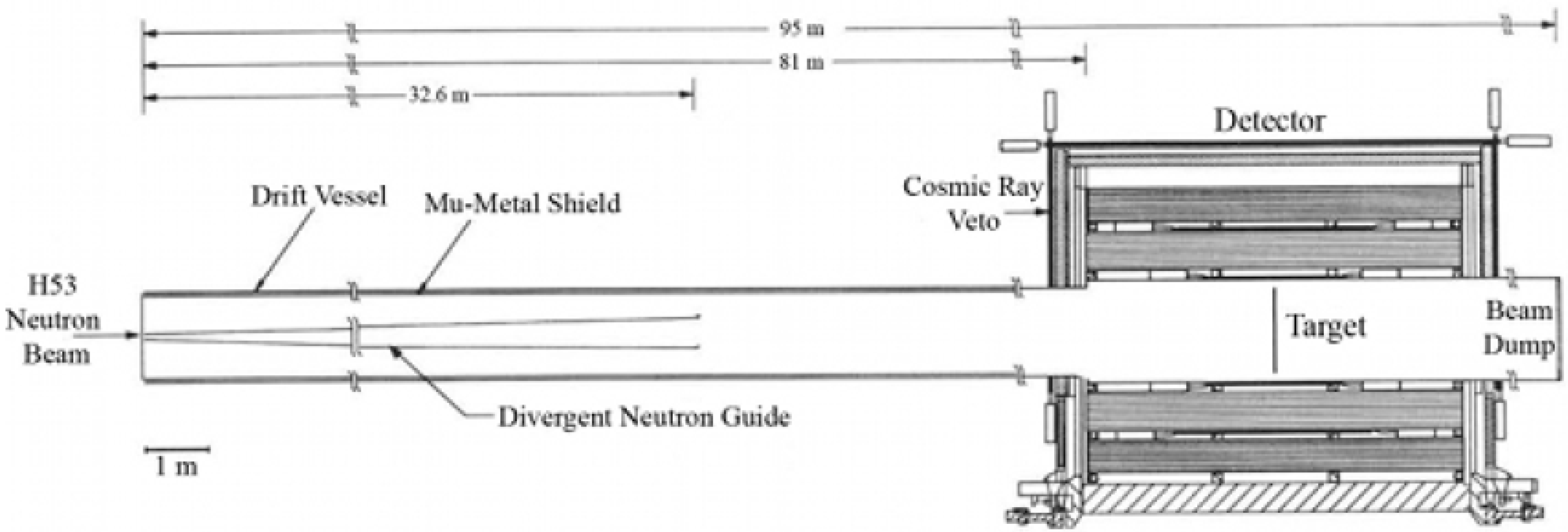
$\Rightarrow$ Suppression: $\left(\frac{\delta m}{\Delta E}\right)^2 < 10^{-60}$

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.

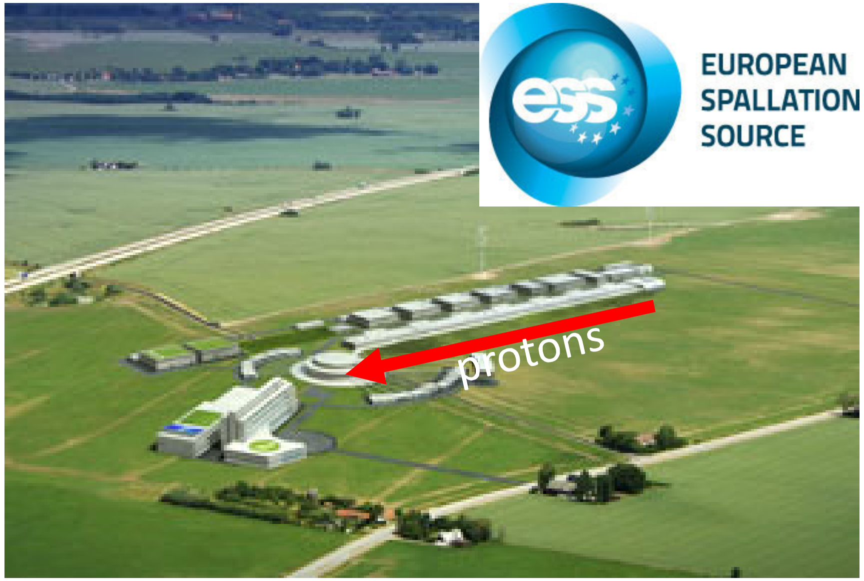
$\Rightarrow \tau_{n\to\bar{n}} > 0.86\times10^{8}$s.

The European Spallation Source

High intensity spallation neutron source

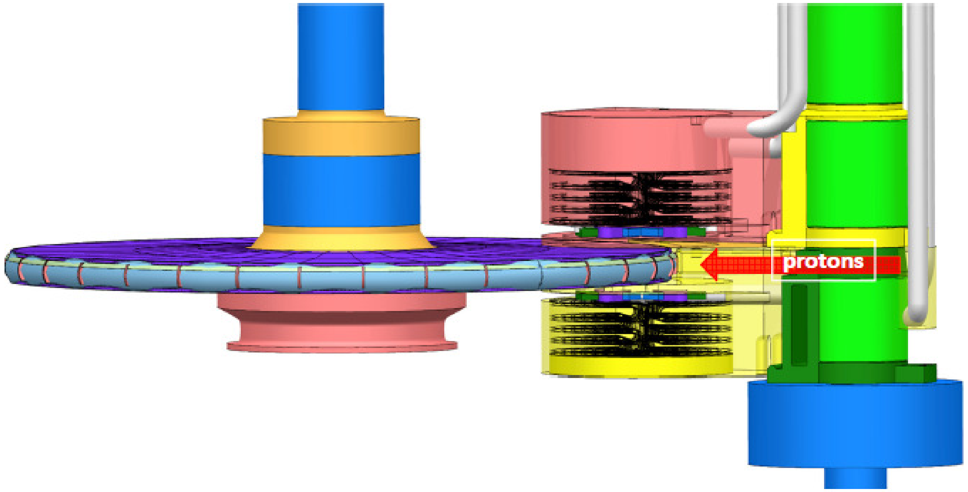
Multidisplinary research centre with 17 European nations participating.

Lund, Sweden.
Start operations in 2019.

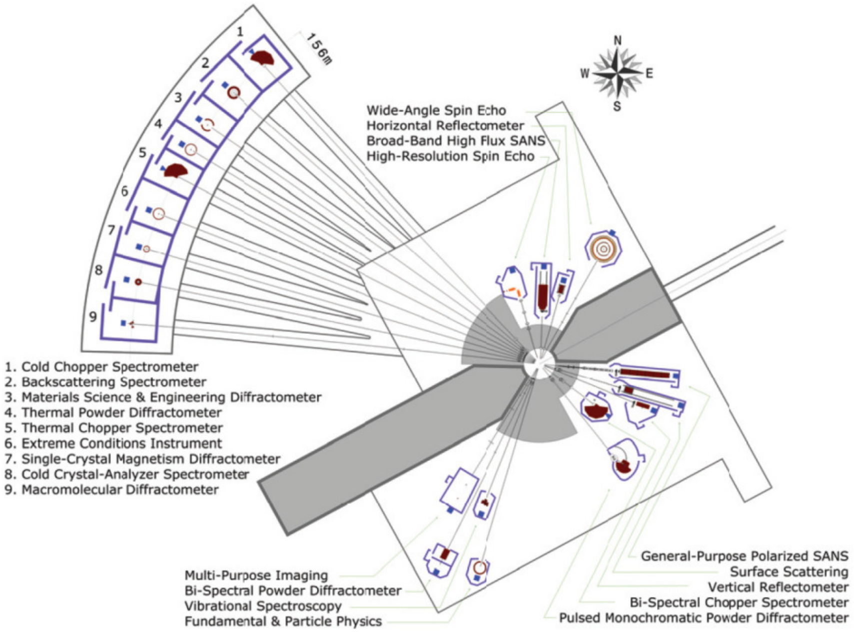


2 GeV protons (3ms long pulse, 14 Hz) hit rotating tungsten target.

Cold neutrons after interaction with moderators.

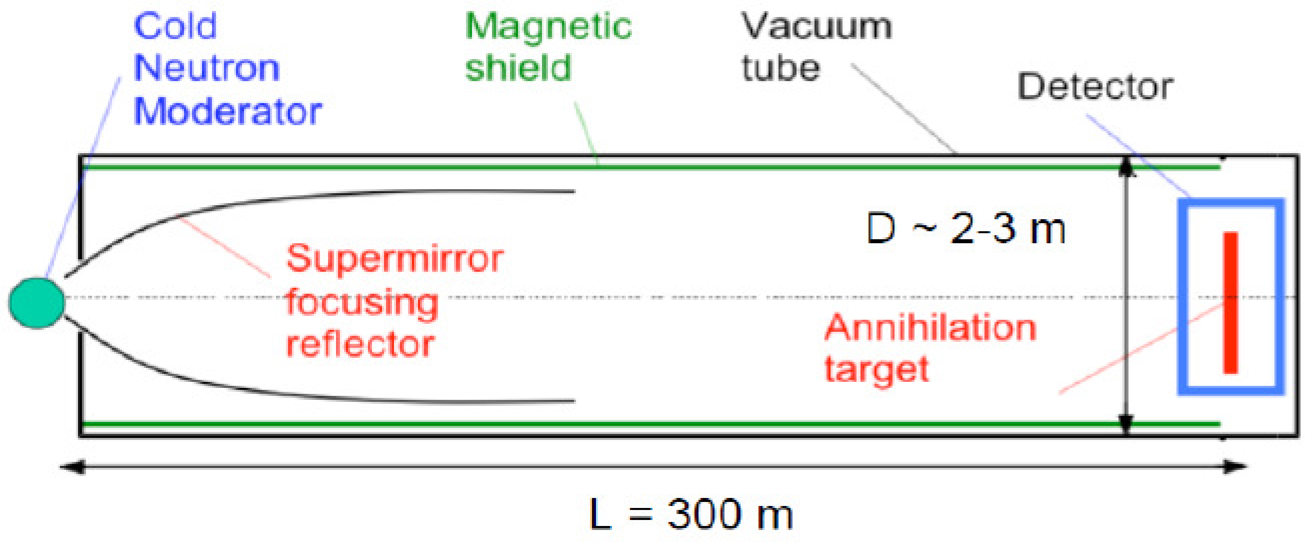


The European Spallation Source



~ 22 instruments/experiments with capability for more.

Overview of the Experiment

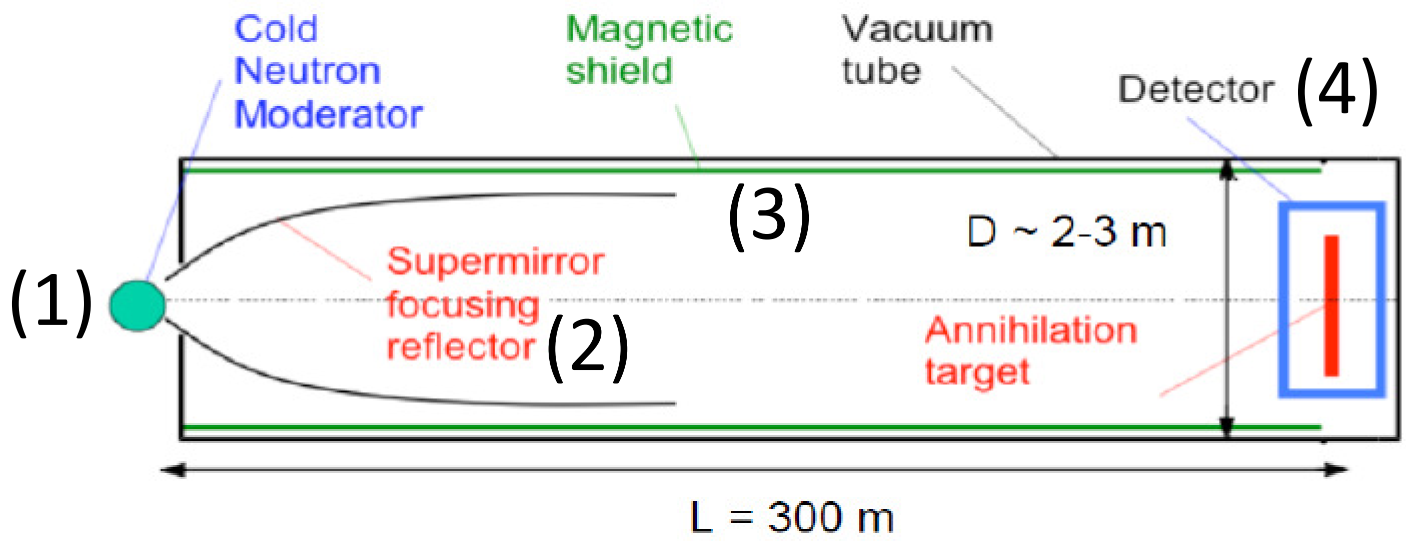


Sensitivity $= (\text{free neutron flux at target}) \times P(n \rightarrow \bar{n}) \propto N_n t^2$

- 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.

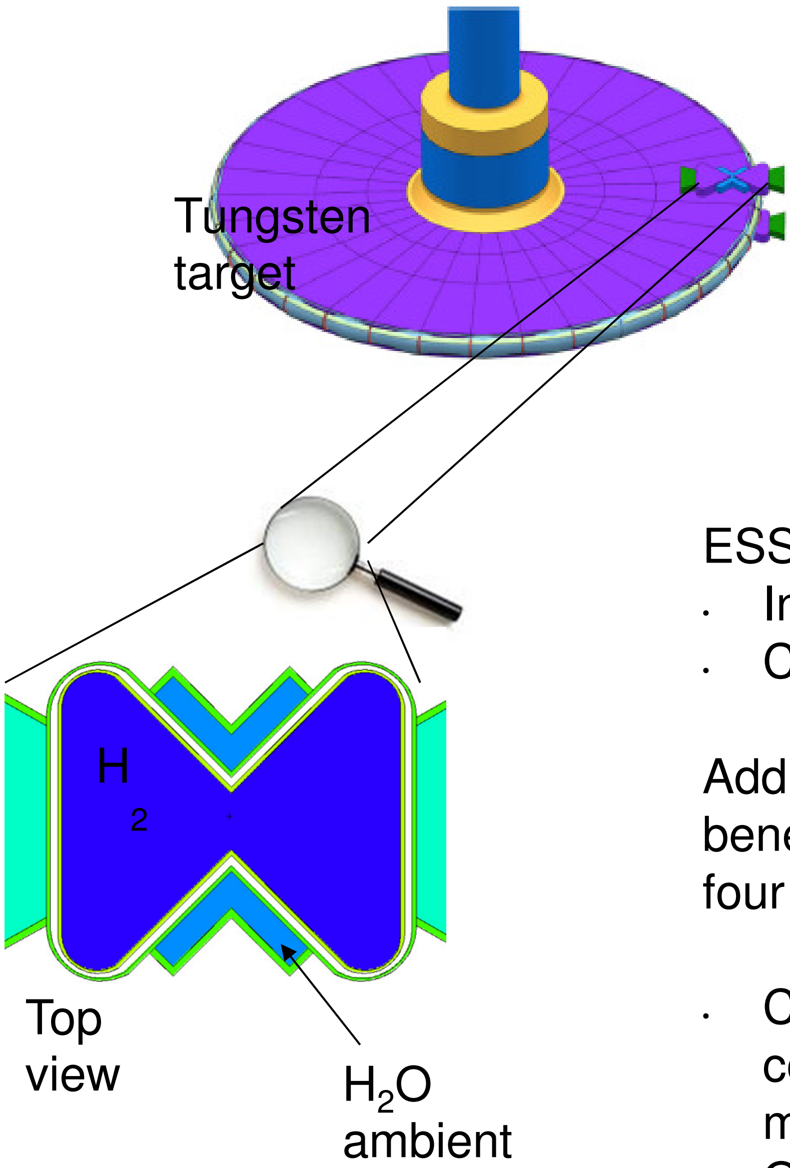
Increase in sensitivity for $P_{n\bar{n}}$ ~ 10^3 compared to previous experiment (ILL)

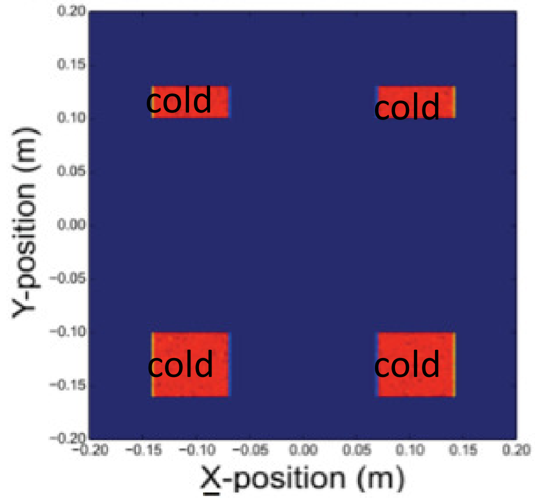
- Neutron guiding, larger opening angle, higher flux, particle ID technologies, running time.



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

Neutronics (1)



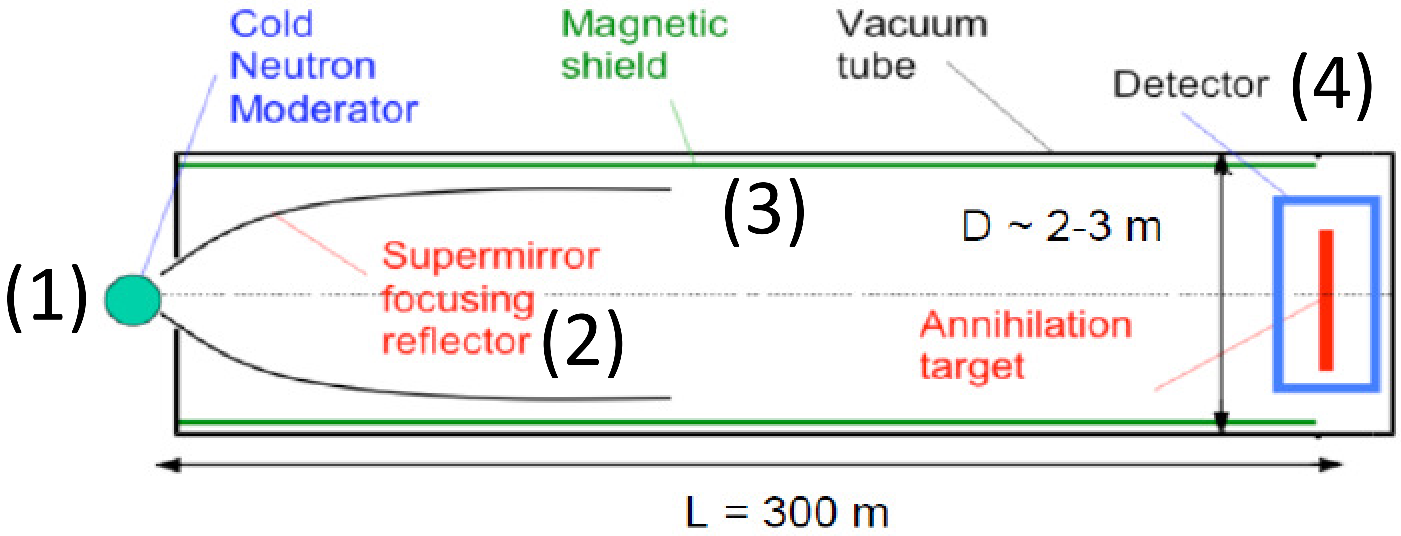


ESS moderators will be of “butterfly” design

- Increase cold yield
- Convenient beam extraction

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

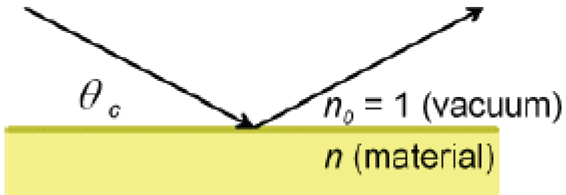
- Conventional point-to-point focusing of a cold neutron beam using ellipsoidal mirrors inefficient.
- Ongoing studies on neutron optics



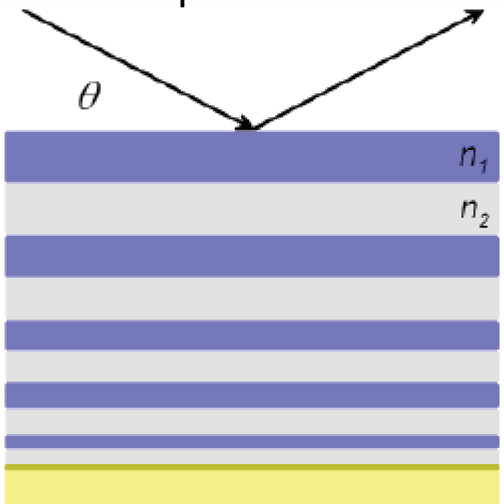
Cold
Neutron
Moderator
Magnetic
shield
Vacuum
tube
Detector
(4)
(3)
D ~ 2-3 m
(1)
Supermirror
focusing
reflector
(2)
Annihilation
target
L = 300 m

Neutron supermirror

Smooth surface

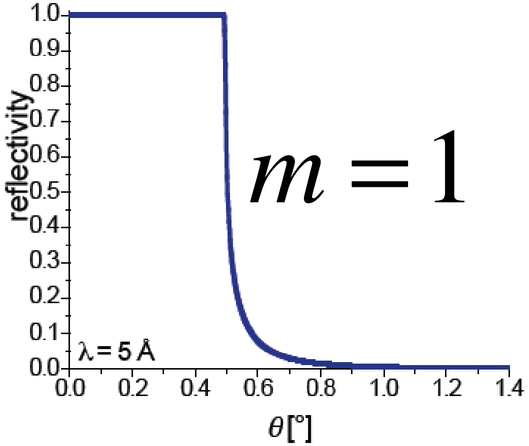


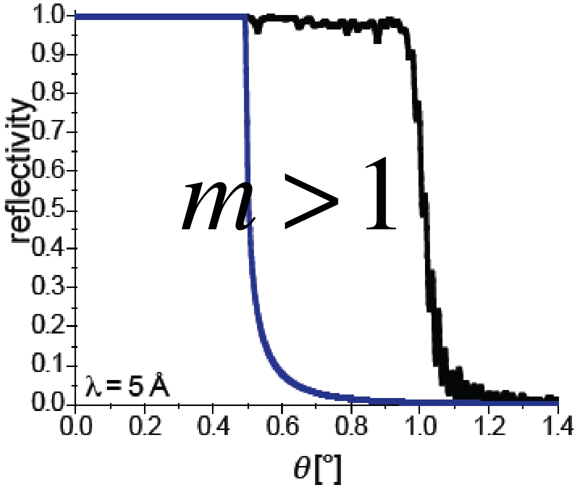
Supermirror



θ_c =Critical angle for total internal reflection

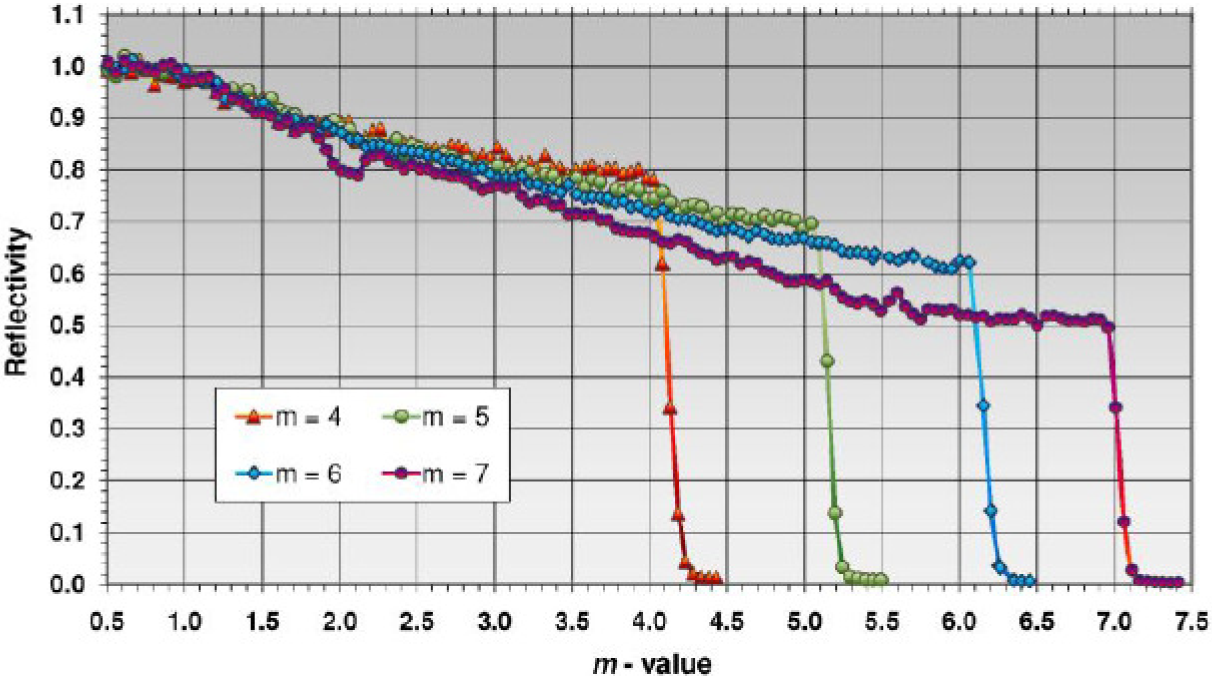
$\theta_c \rightarrow m\theta_C^{Ni}$





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

Commercial supermirrors



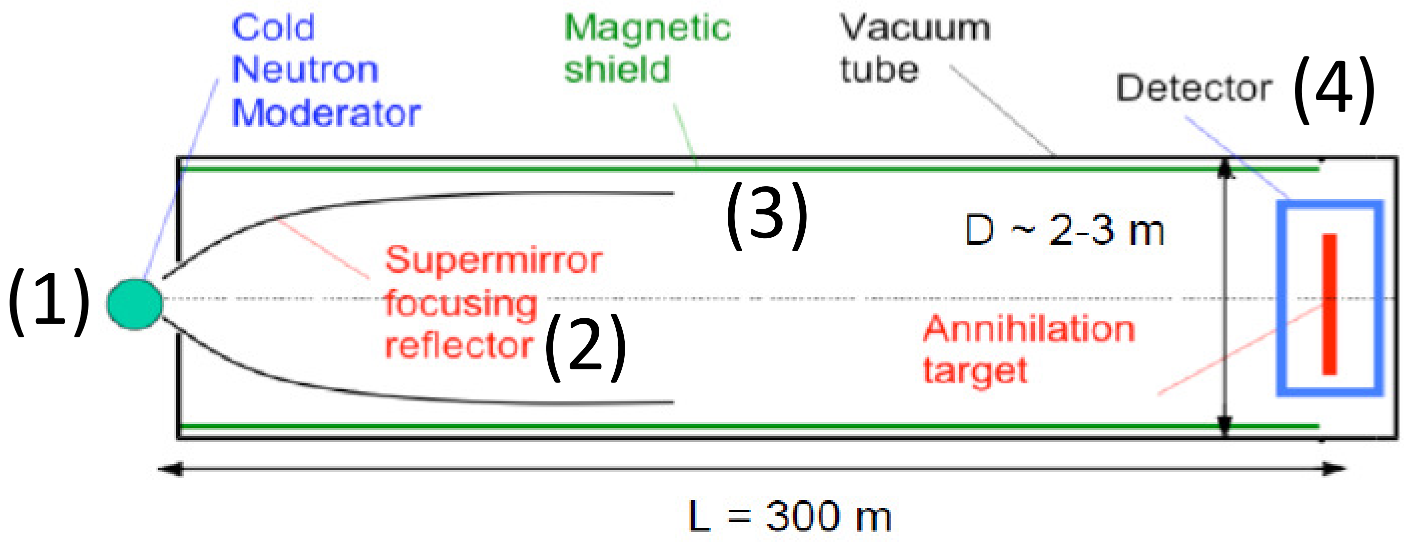
Commercial supermirrors with $m \sim 7$

Acceptance for straight guide $\propto m^2$

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

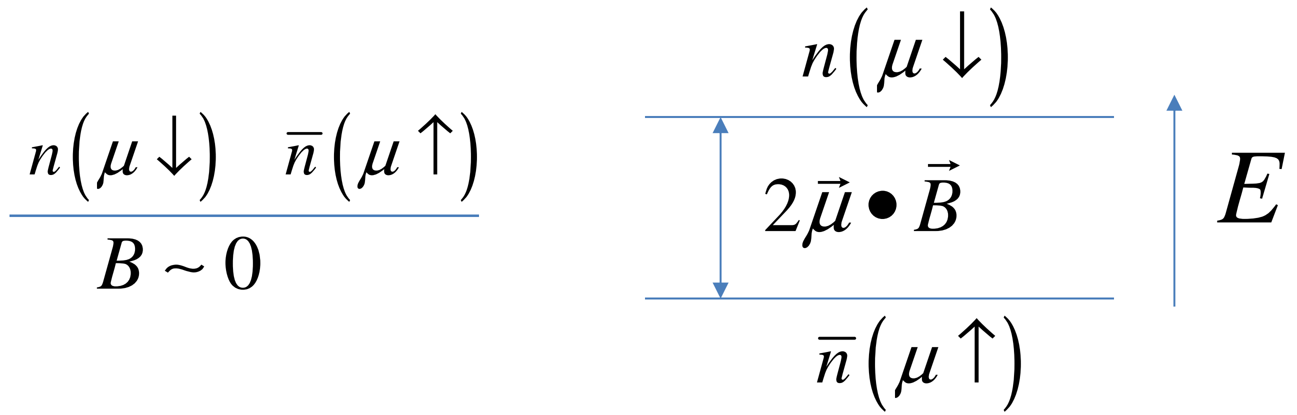
Increase from use of focusing reflector and optimised mirror arrays.

Crucial contribution to increase of sensitivity wrt ILL.



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

The need for magnetic shielding



Degeneracy of $n, \bar{n}$ broken in B-field due to

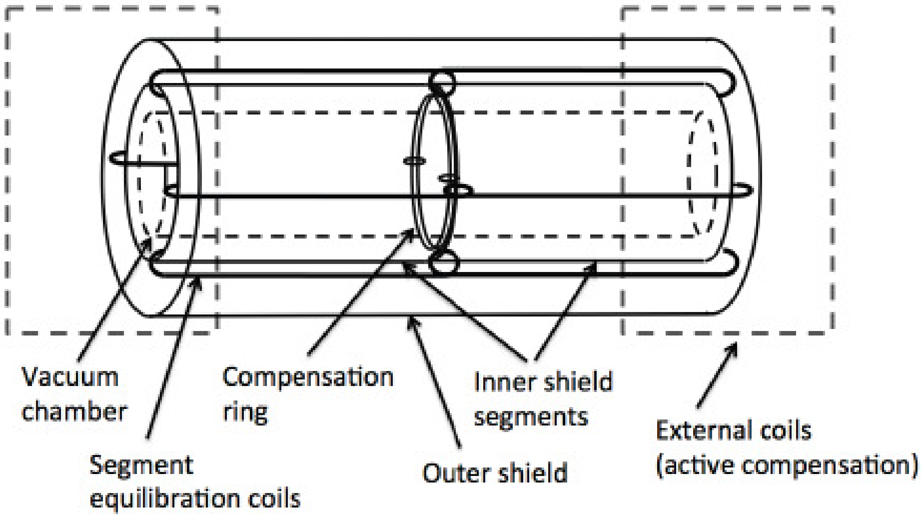
dipole interactions: $\Delta E = 2\vec{\mu}\bullet\vec{B}$

Flight time ≤ 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

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

Maybe shielding isn't needed

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

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

S. Gardner* and E. Jafari

Department of Physics and Astronomy, University of Kentucky, Lexington, Kentucky 40506-0055, USA

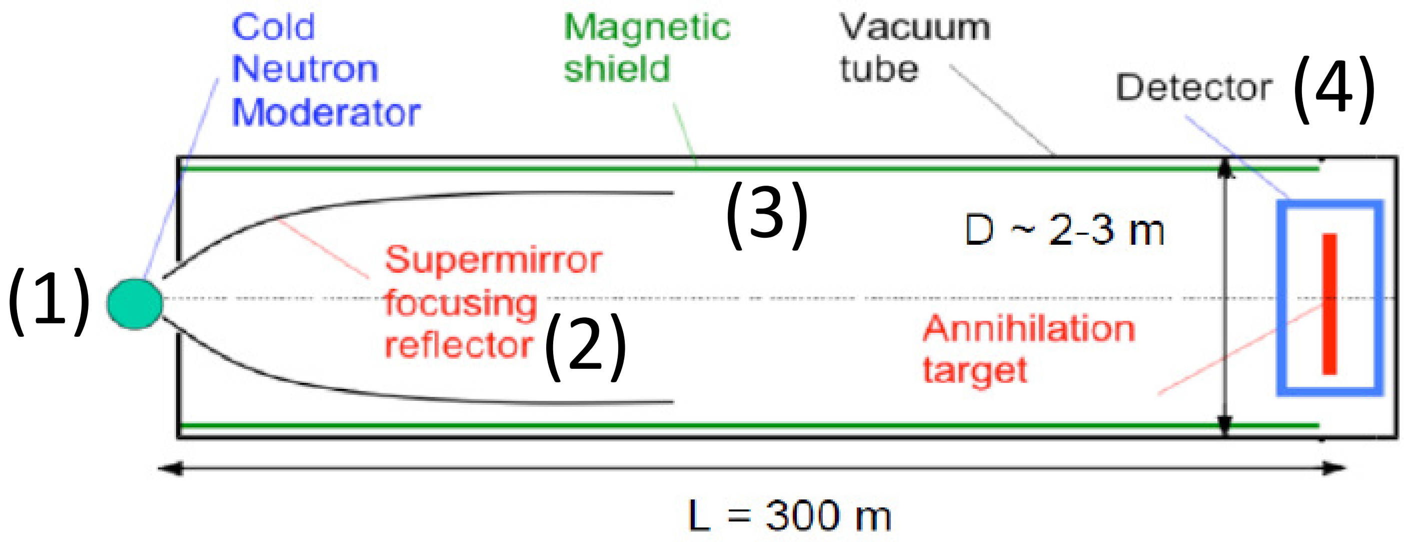
(Received 14 August 2014; revised manuscript received 15 February 2015; published 22 May 2015)

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.

Overview of the Experiment

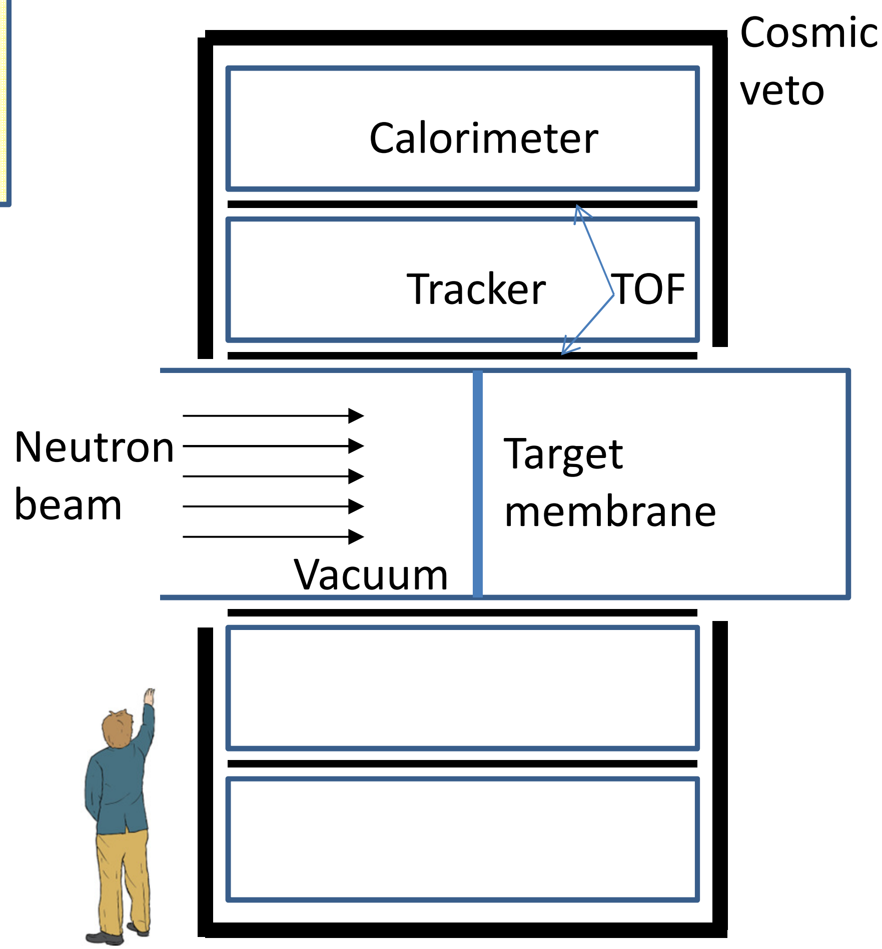


(4) Detector

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

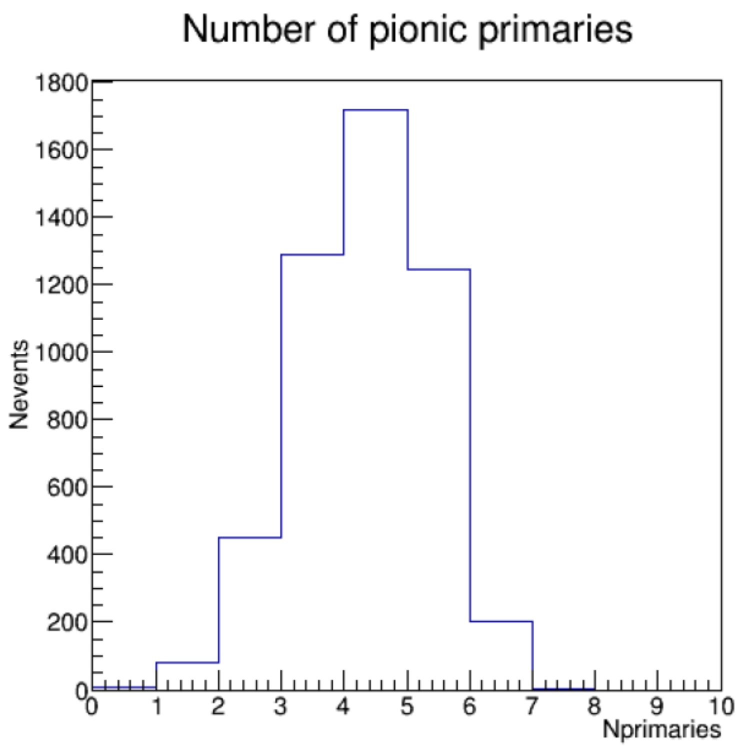


GENIE: NNBar Final State Primaries

Preliminary

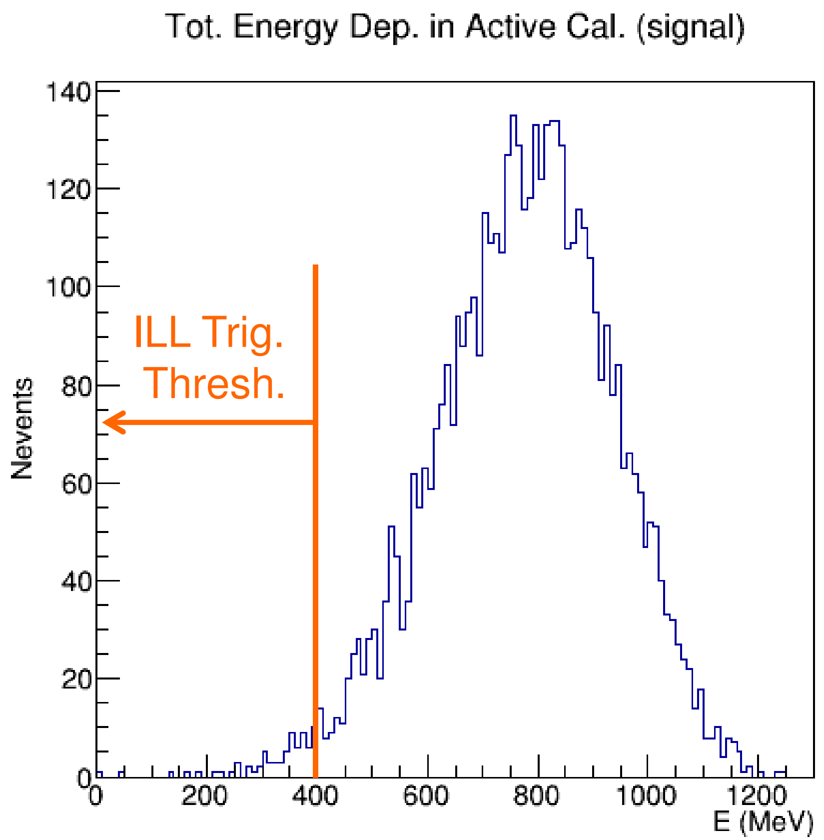
Final state list prepared by R. W. Pattie

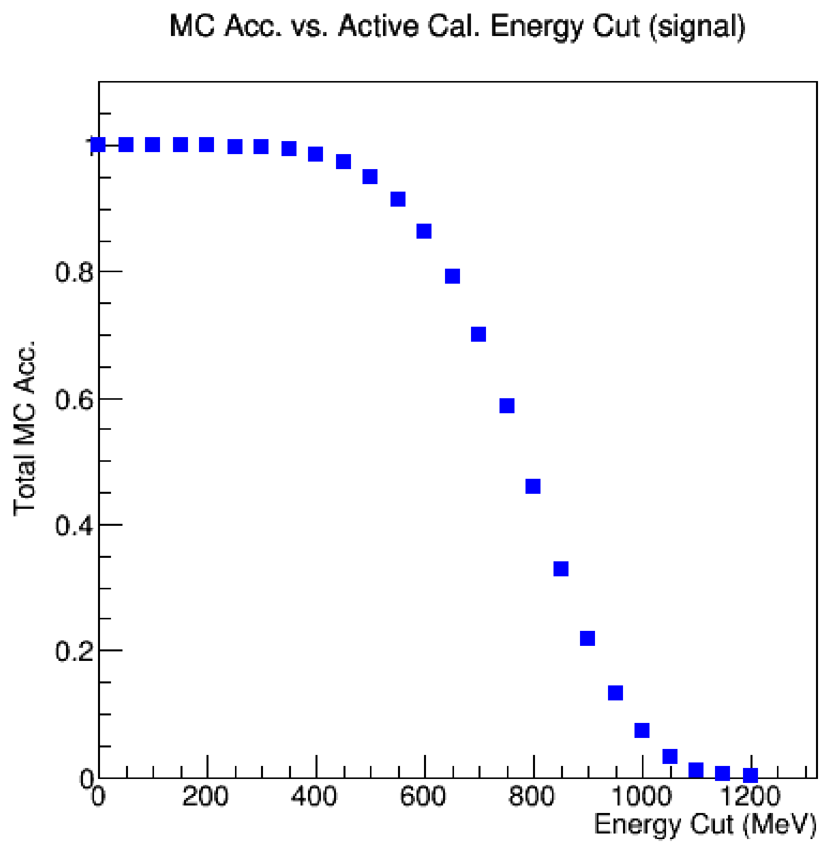
GENIE-2.0.0: intranculear propagation based on INTRANUKE
C.Andreopoulos et al., The GENIE Neutrino Monte Carlo Generator, Nucl.Instrum.Meth.A614:87-104,2010.



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%

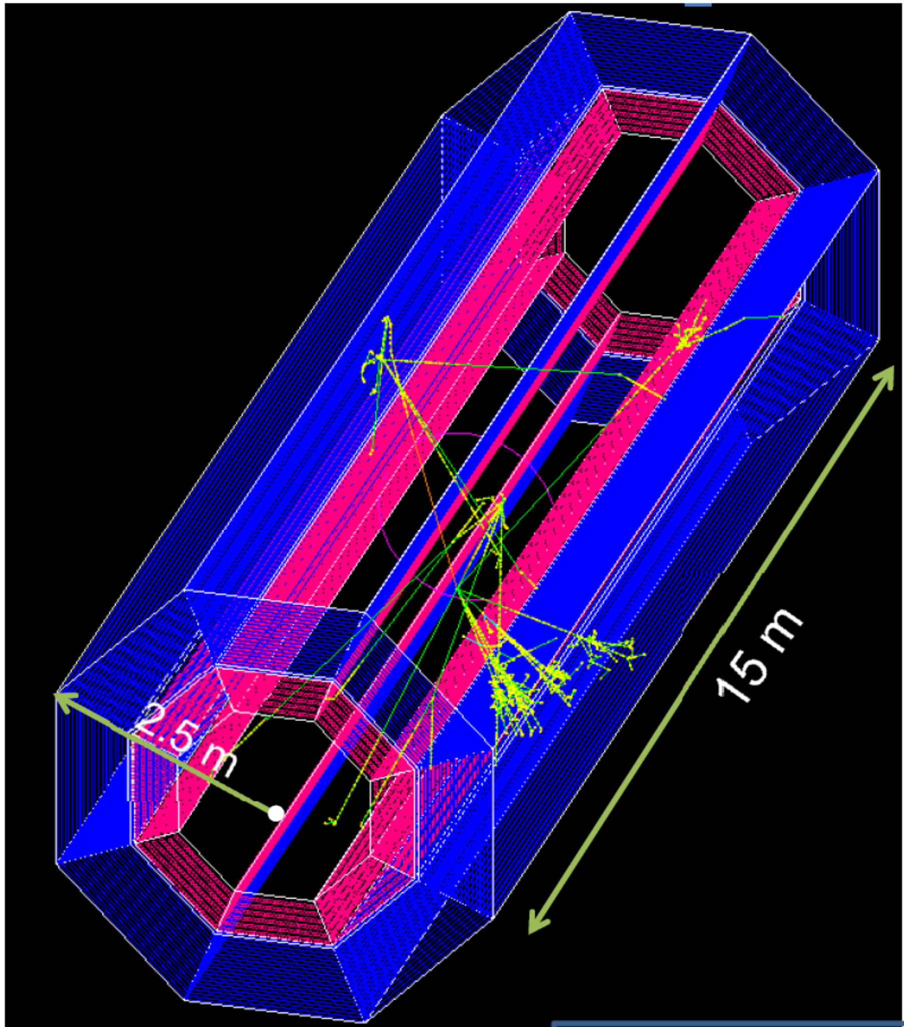
Energy Threshold Acceptance (Signal)



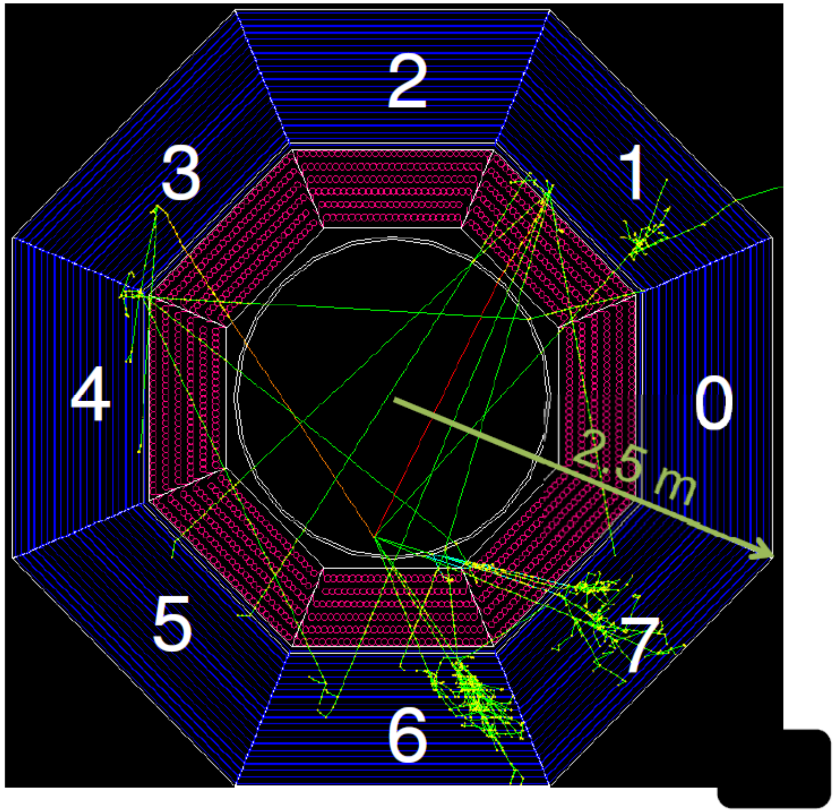


A. R. Young, D. G. Phillips II, R. W. Pattie Jr.

Annihilation event



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



Collaboration and approximate timescales

Several workshops (CERN, Lund, Gothenburg)
Collaboration formed – interim spokesperson G. Broojimans
Expression of Interest submitted to ESS.
Signatories from 26 institutes , 8 countries.
Sweden: Stockholm, Uppsala, Lund, Chalmers.
More collaborators are welcome!

ESS	$n\bar{n}$
	2019
Commissioning, Intensity ramp, early experiments	Construction, commissioning, early data-taking
	2023
Initial user program	Physics runs
	2026
Routine operations	End run, complete analysis

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

- The search for neutron-antineutron oscillations addresses 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 submitted
- Provisional schedule made.

Brightness		≥ 1
Moderator Temperature	<TOF> driven by colder neutrons, ~quadratic (t^2)	≥ 1
Moderator Area	Needs large aperture	2
Angular Acceptance	2D, so quadratic sensitivity	40
Length	Scale with t^2, so L^2	5
Run Time	ILL run was 1 year	3
Total		≥ 1000

x 1000 in probability, reach $\tau \sim 2\text{-}3 \times 10^9$ s

(simulations with various moderator options underway)

Potential gains

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

Baryon number violation searches

Few searches for

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

τ limits $\sim 10^{30} - 10^{34}$ yrs

τ limit from new experiment

$\sim 10^{35}$ 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

$p \to e^+\gamma$	> 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

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

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

BNV searches

RPP

BARYON NUMBER

$\Gamma(Z \to pe)/\Gamma_{\text{total}}$		$<1.8 \times 10^{-6}$, CL = 95%
$\Gamma(Z \to p\mu)/\Gamma_{\text{total}}$		$<1.8 \times 10^{-6}$, CL = 95%
$\Gamma(\tau^- \to \overline{p}\gamma)/\Gamma_{\text{total}}$		$<3.5 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \overline{p}\pi^0)/\Gamma_{\text{total}}$		$<1.5 \times 10^{-5}$, CL = 90%
$\Gamma(\tau^- \to \overline{p}2\pi^0)/\Gamma_{\text{total}}$		$<3.3 \times 10^{-5}$, CL = 90%
$\Gamma(\tau^- \to \overline{p}\eta)/\Gamma_{\text{total}}$		$<8.9 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \overline{p}\pi^0\eta)/\Gamma_{\text{total}}$		$<2.7 \times 10^{-5}$, CL = 90%
$\Gamma(\tau^- \to \Lambda\pi^-)/\Gamma_{\text{total}}$		$<7.2 \times 10^{-8}$, CL = 90%
$\Gamma(\tau^- \to \overline{\Lambda}\pi^-)/\Gamma_{\text{total}}$		$<1.4 \times 10^{-7}$, CL = 90%
$\Gamma(D^0 \to pe^-)/\Gamma_{\text{total}}$	[s]	$<1.0 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to \overline{p}e^+)/\Gamma_{\text{total}}$	[t]	$<1.1 \times 10^{-5}$, CL = 90%
$\Gamma(B^+ \to \Lambda^0\mu^+)/\Gamma_{\text{total}}$		$<6 \times 10^{-8}$, CL = 90%
$\Gamma(B^+ \to \Lambda^0 e^+)/\Gamma_{\text{total}}$		$<3.2 \times 10^{-8}$, CL = 90%
$\Gamma(B^+ \to \overline{\Lambda}^0\mu^+)/\Gamma_{\text{total}}$		$<6 \times 10^{-8}$, CL = 90%
$\Gamma(B^+ \to \overline{\Lambda}^0 e^+)/\Gamma_{\text{total}}$		$<8 \times 10^{-8}$, CL = 90%
$\Gamma(B^0 \to \Lambda_c^+\mu^-)/\Gamma_{\text{total}}$		$<1.8 \times 10^{-6}$, CL = 90%
$\Gamma(B^0 \to \Lambda_c^+ e^-)/\Gamma_{\text{total}}$		$<5 \times 10^{-6}$, CL = 90%
p mean life	[u]	$>2.1 \times 10^{29}$ years, CL = 90%

A few examples of proton or bound neutron decay follow. For limits on many other nucleon decay channels, see the Baryon Summary Table.

$\tau(N \to e^+\pi)$	> 2000 (n), > 8200 (p) $\times 10^{30}$ years, CL = 90%
$\tau(N \to \mu^+\pi)$	> 1000 (n), > 6600 (p) $\times 10^{30}$ years, CL = 90%
$\tau(N \to e^+K)$	> 17 (n), > 1000 (p) $\times 10^{30}$ years, CL = 90%
$\tau(N \to \mu^+K)$	> 26 (n), > 1600 (p) $\times 10^{30}$ years, CL = 90%

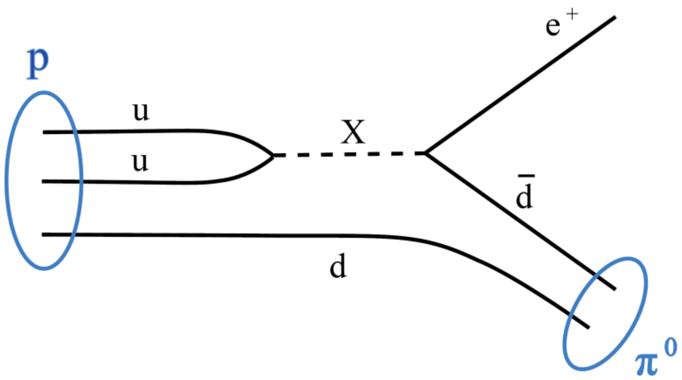
L and B violated

limit on $n\overline{n}$ oscillations (free n)		$>0.86 \times 10^8$ s, CL = 90%
limit on $n\overline{n}$ oscillations (bound n)	[v]	$>1.3 \times 10^8$ s, CL = 90%

B violated

Poor experimental coverage of ”pure” B violation tests

Complementary searches for BNV and LNV

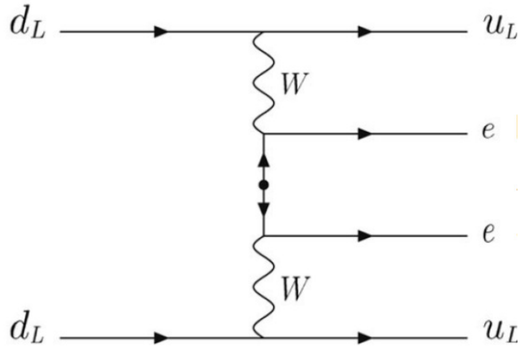


Single nucleon decay

Eg unification models

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

$\Delta(B - L) = 0$

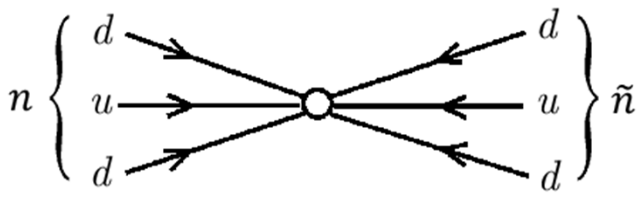


Neutrinoless 2β-decay

Eg seesaw mechanism for light ν

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

$\Delta|(B - L)| = 2$



$n \to \bar{n}$

Eg Unification models

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

$\Delta|(B - L)| = 2$

Each search tests complementary conservation laws.

Neutrinoless double β-decay $\Leftrightarrow$ $n \to \bar{n}$ linked under B - L violation.

Eg Left-right symmetric models.

$n \to \bar{n}$ in a SUSY framework

Reduced particle content: $u, d + \tilde{g}, \tilde{d}, \tilde{s}, \tilde{b}$

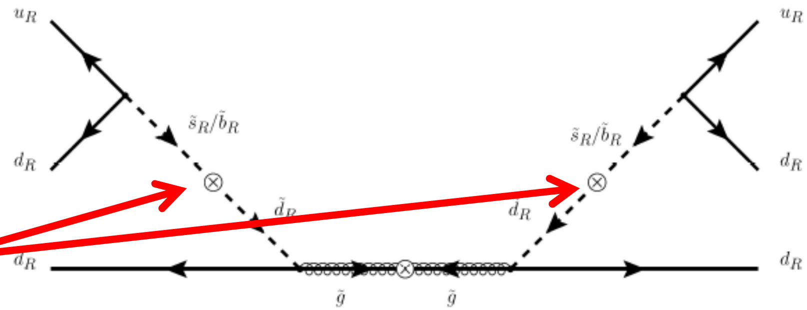
$$\tau_{n\bar{n}} = \frac{1}{C \langle \bar{n} | \mathcal{O}_1 | n \rangle} \quad ; \quad C = \frac{16}{3} \frac{g_s^2}{m_{\tilde{g}}} \left| \frac{\lambda''_{11k} m^2_{\tilde{d}_R(\tilde{s}_R, \tilde{b}_R)}}{m^2_{\tilde{d}_R} m^2_{\tilde{s},\tilde{b}_R}} \right|$$

$\Rightarrow$ Yukawa coupling: λ''_{11k}.

$$\lambda''_{ijk} = -\lambda''_{ikj} \Rightarrow \lambda''_{111} = 0$$

$\Rightarrow n\bar{n}$ steered by $\lambda''_{112}, \lambda''_{113}$.

$\Rightarrow$ Flavour mixing $\left[\tilde{s} \to \tilde{d}, \tilde{b} \to \tilde{d} \right]$



$\Rightarrow$ Mixing parameters: eg $\left(\delta^d_{RR} \right)_{1k} = \dfrac{m^2_{\tilde{d}_R(\tilde{s}_R, \tilde{b}_R)}}{m^2_{\tilde{d}_R}} \neq 0$