次世代の中性子-反中性子振動実験

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n-n̄ oscillation

	Neutron	Anti-neutron
Mass [MeV/c^2]	939.5654133(58)	939.565560(81)
Ele. Charge [10^{-21}e]	-0.2±0.8	(0)
Spin^{Parity}	$1/2^+$	$1/2^+$
Mag. Moment [μN]	-1.91304273(45)	(+1.91)
Quark Content	udd	$\overline{udd}$
Baryon Number	+1	-1

* PDG2021

Anti-neutron $\bar{n}$ $\psi_{\bar{n}} \equiv C\psi_n \equiv i\sigma_2\psi_n^*$

Cf. Mirror-neutron n' $\psi_{n'} = P\psi_n$

ΔB = 2

n ↔ n̄ (ΔB = 2) is allowed if baryon-number is not conserved;
i.e. neutron and antineutron are **Majorana fermions**.

$$\psi_n \equiv \psi_{\bar{n}} \equiv C\psi_n$$

Note.

- Only neutral fermions can be Majorana (but not necessary).
- SUSY partners ($\tilde{\gamma}$, $\tilde{Z}$, $\tilde{g}$) of neutral gauge bosons should be Majorana.

Grand Unified Theory

GWS standard model; $SU(3)_c \times SU(2)_L \times U(1)_Y$

Minimal SU(5) ; $SU(5) \rightarrow SU(3)_c \times SU(2)_L \times U(1)_Y$

- Proton decay with τ_p=$10^{30\sim32}$y excluded by Kamiokande & SK
- Finite m_ν
- (Dark matter , dark energy, hierarchy problem, …)

Minimal SUSY SU(5) ?

- No evidence in LHC

Non-SUSY SO(10) ?

- Heavy right-handed neutrino can be included in 16-rep.
  → Seesaw for light neutrinos
- Compatible with long τ_p and large θ_{13}

Standard model; $SU(3)_c \times SU(2)_L \times U(1)_Y$

Minimal SU(5); $SU(5) \supset SU(3)_c \times SU(2)_L \times U(1)_Y \rightarrow SU(3)_c \times U(1)_{EM}$

SO(10) (Spin(10)); $SO(10) \supset SO(6) \times SO(4)$

$$SO(6) \supset SU(4) \supset SU(3)_c \times U(1)_{\boldsymbol{B\text{-}L}}$$

$$SO(4) \supset SU(2) \times SU(2)'$$

$$\downarrow \qquad \downarrow$$

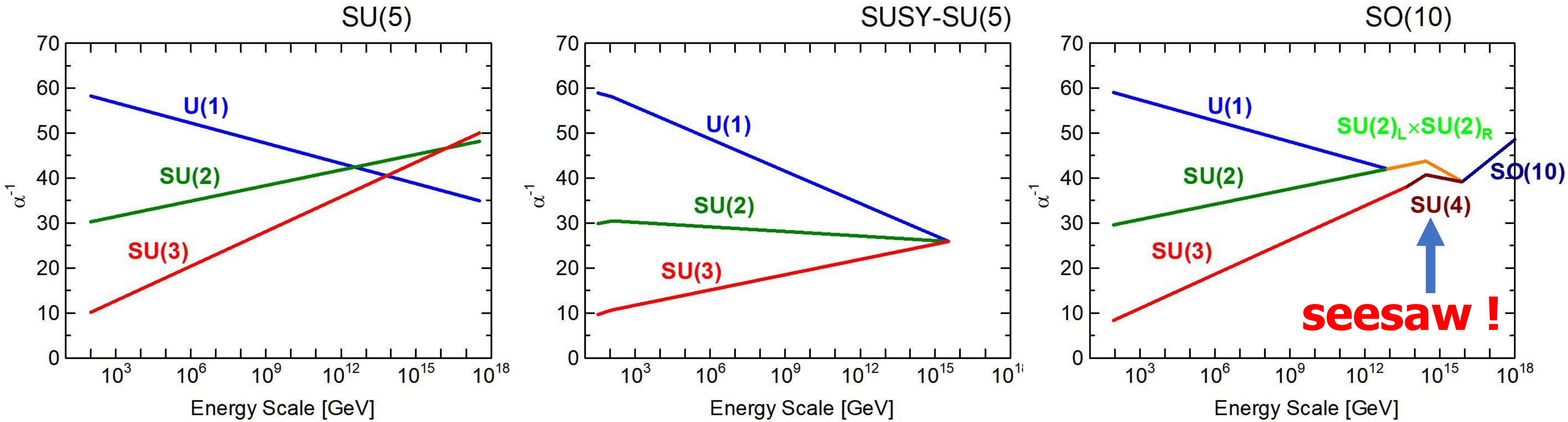
$$SU(2)_L \quad SU(2)_{\boldsymbol{R}}$$

$$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B\text{-}L} \rightarrow SU(3)_c \times U(1)_{EM}$$

R.N. Mohapatra & R.E. Marshak, PRL44, 1316 (1980)

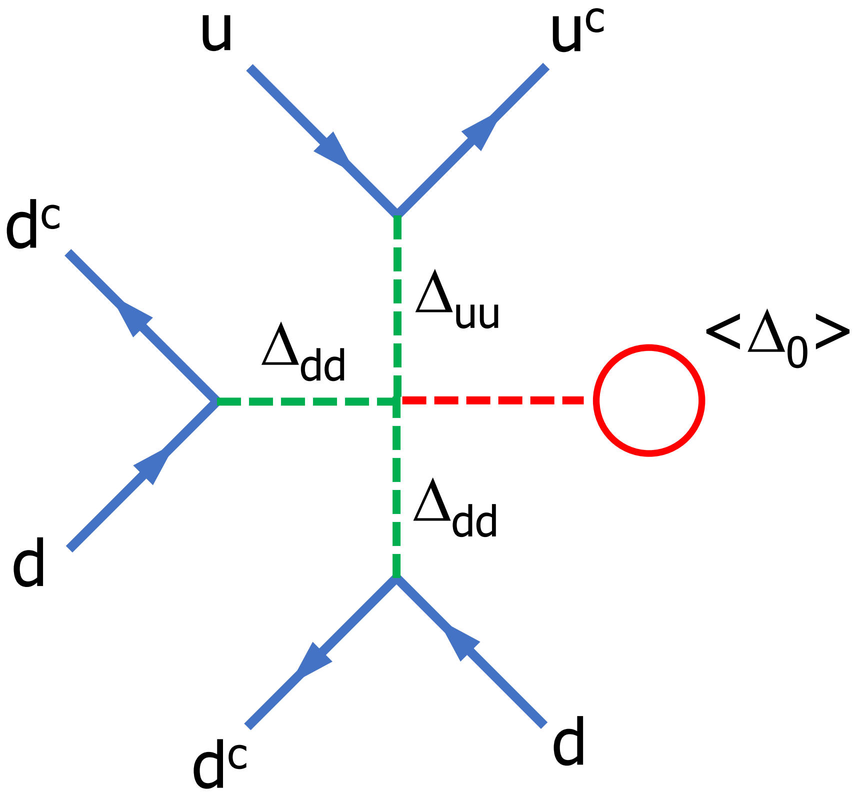
- ✓ Conservation of |B-L|
- ✓ Left-Right symmetric structure in weak interaction

Unification of Coupling Constants



$$\left| m_{\nu,L} \right| \sim \frac{m_D^2}{m_{\nu,M}} \sim \frac{100^2}{10^{15}} \ [\mathrm{GeV}] \sim 10 \ [\mathrm{meV}]$$

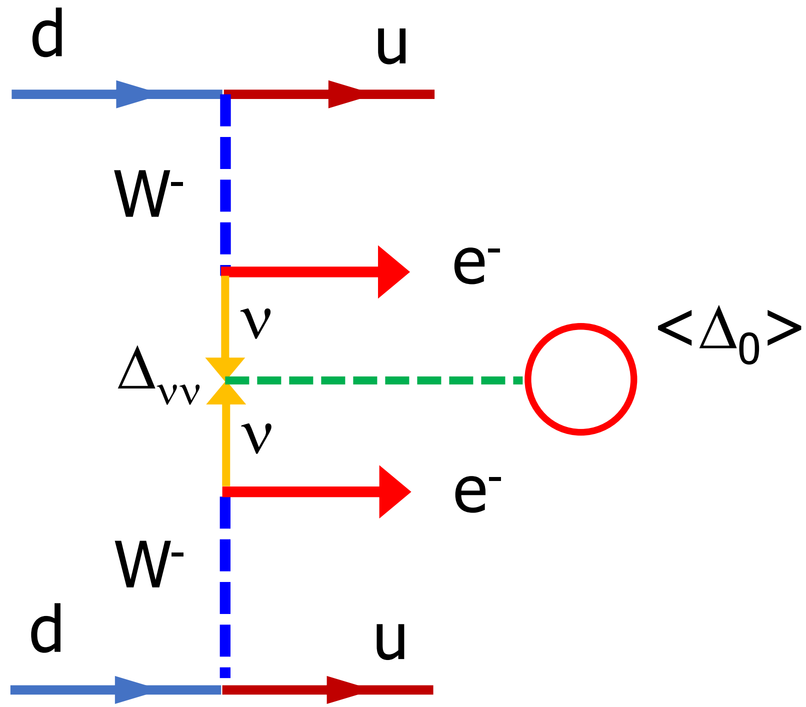
n-$\bar{n}$



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

$$\Delta\left(B - L\right) = -2$$

0νββ



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

$$\Delta\left(B - L\right) = +2$$

Type of GUT	Osc. period $\tau = 10^6 \sim 10^{10}$ sec ?
$SU(2)_L \times U(1)_Y$ (GWS)	forbidden
minimal SU(5)	forbidden
$SU(4)_C \times SU(2)_L \times SU(2)_R$	yes
SO(10)	no
SO(10) with low-energy $SU(4)_C$	yes
E_6	no
SUSY-SU(5)	too rapid
SUSY-E_6	yes

(R.N.Mohapatra, NIM A284 (1989) 1)

$n \rightarrow \bar{n}$ conversion probability

$$i\frac{\partial}{\partial t}\begin{pmatrix}\psi_n(t)\\ \psi_{\bar{n}}(t)\end{pmatrix}=\begin{pmatrix}E_n-\boldsymbol{\mu}_n\cdot\mathbf{B}-i\Gamma_\beta/2 & \varepsilon\\ \varepsilon & E_n+\boldsymbol{\mu}_n\cdot\mathbf{B}-i\Gamma_\beta/2\end{pmatrix}\begin{pmatrix}\psi_n(t)\\ \psi_{\bar{n}}(t)\end{pmatrix}$$

For $\psi_n(0)=1,\ \psi_{\bar{n}}(0)=0,$

$$\left|\psi_{\bar{n}}(t)\right|^2=\frac{4\varepsilon^2}{\omega^2+4\varepsilon^2}\exp\left(-\Gamma_\beta t\right)\cdot\sin^2\left(\frac{1}{2}\sqrt{\omega^2+4\varepsilon^2}\,t\right)$$

where $\omega\equiv 2\left|\boldsymbol{\mu}_n\cdot\mathbf{B}\right|$

--- conversion is suppressed by external magnetic field.

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

Cold neutron; E_n = 2meV (T=25K) , $\Phi_n = 1.25 \times 10^{11}$ n/sec

Flight path ; L_{TOF} = 76.5m, t_{TOF} = 0.1 sec

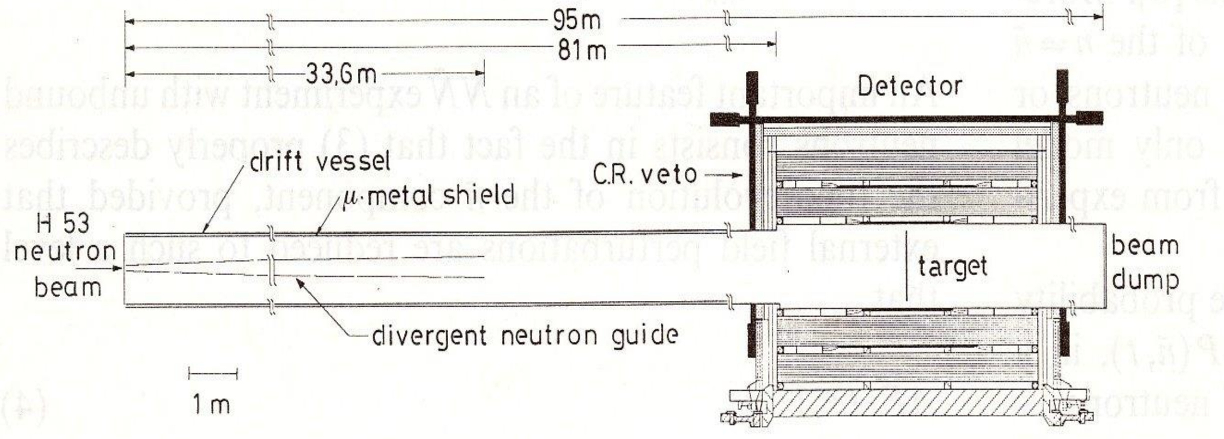
P < 0.01 Pa, B < 10 nT

Target; graphite film (130μm) Detector efficiency ; $\varepsilon = 0.52$

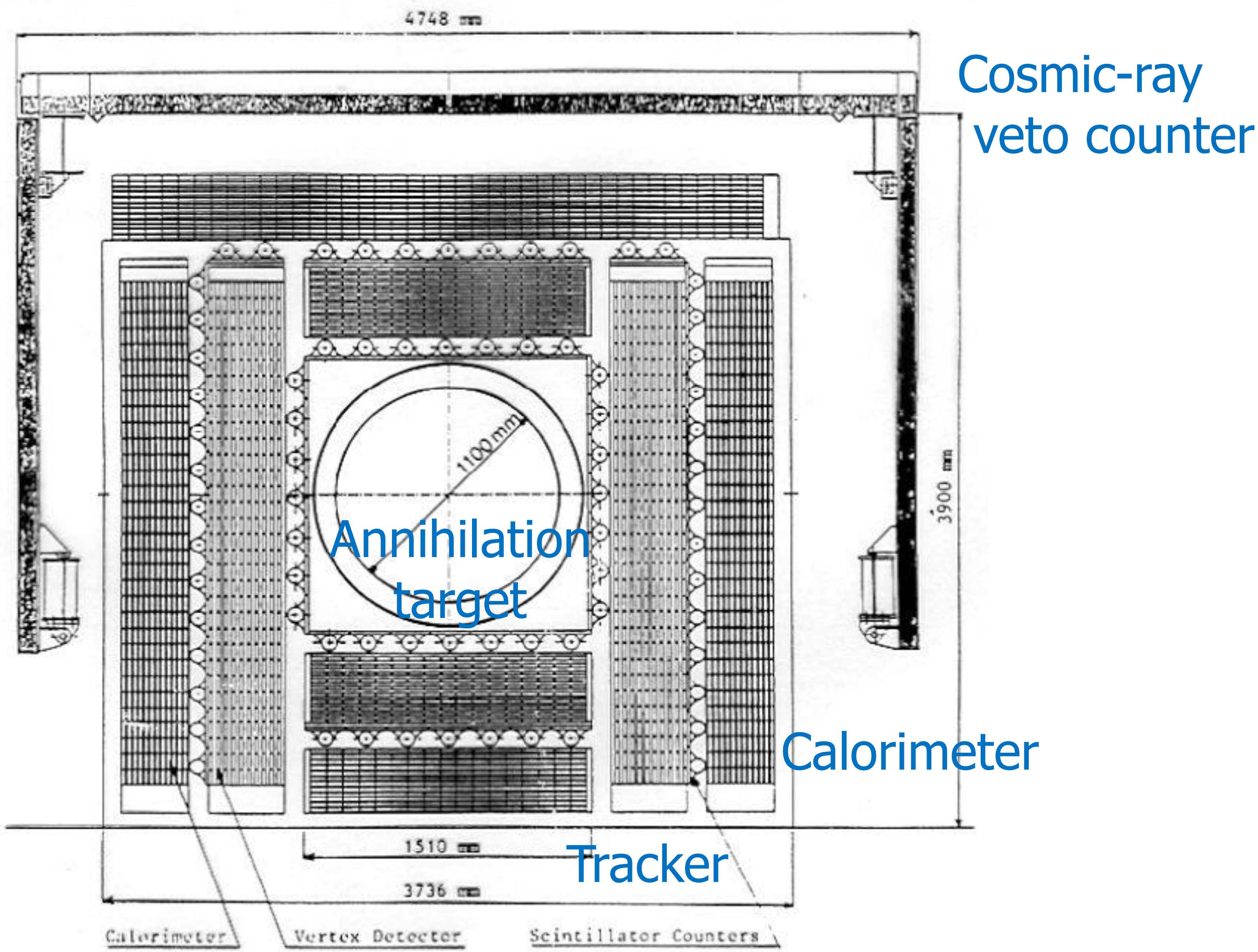
Measurement time ; $T_{mes.} = 2.4 \times 10^{7}$ sec

$$P_{n-\bar{n}} \approx \left(\frac{t_{TOF}}{\tau_{n-\bar{n}}} \right)^2 ,$$

$$Y_{\bar{n}} = \varepsilon \cdot \Phi_n \cdot P_{n-\bar{n}} \cdot T_{mes.}$$



$\tau_{n\text{-}nbar} > 8.6 \times 10^{7}$ sec



$$^{12}\mathrm{C}+\bar{n} \rightarrow X + x\pi \ (\sim 1.8\mathrm{GeV}) \ < \sim 1 \ [\mathrm{event/y}]$$

Intra-nucleus n-$\bar{n}$ conversion

Super-Kamiokande (K. Abe et al., PRD103, 012008 (2021))

proton decay ($\Delta B = 1$) : $p \rightarrow e^+ + \pi_0$ $> 1.6 \times 10^{34}$ year

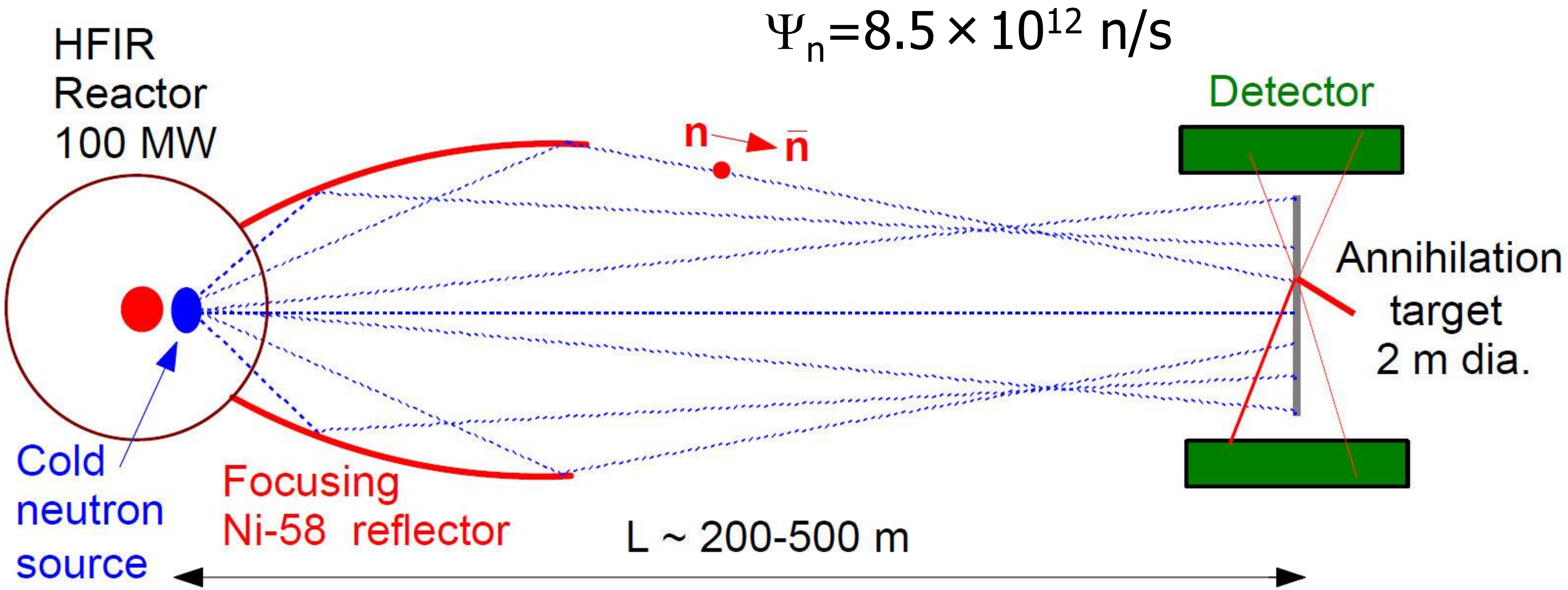
n-$\bar{n}$ oscillation in ^{16}O nucleus ($\Delta B = 2$) : $\tau_{n\text{-}nbar}$ $(^{16}O) > 3.6 \times 10^{32}$ y

$\Rightarrow$ $\tau_{n\text{-}nbar}$ (free) $> 4.7 \times 10^8$ sec (90%CL) $(3 \times 10^8$ sec in 2003)

Huge suppression by nuclear potential !

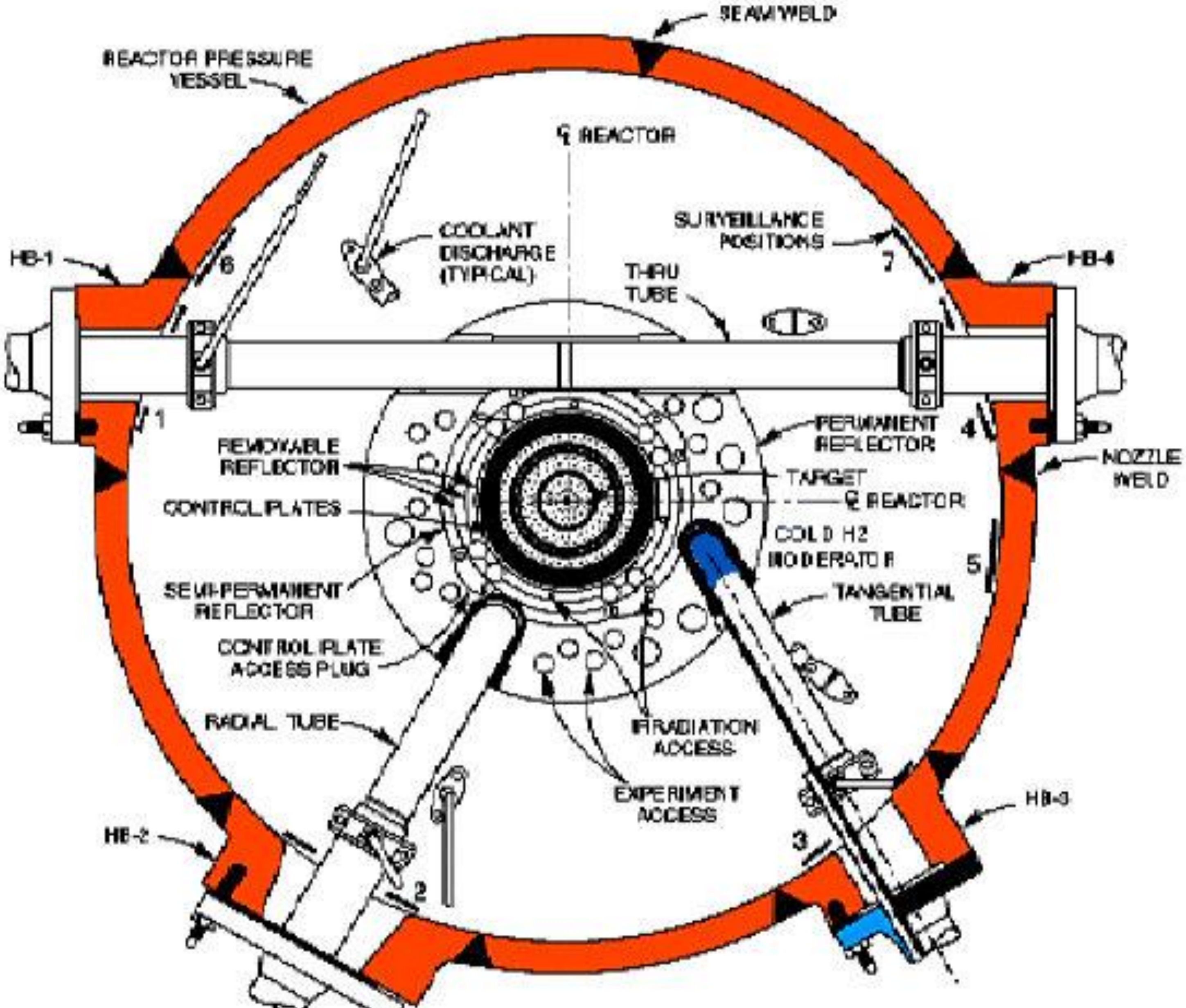
HFIR/ORNL proposal (cold neutron experiment)

Kamyshkov, 2000



$\Rightarrow \quad \tau_{n\text{-}nbar} \sim 3 \times 10^9$ sec within 3 years…

Core structure (planned)



Ultra Cold Neutron

$$P_{n-\bar{n}} \approx \left(\frac{T_s}{\tau_{n-\bar{n}}} \right)^2 \quad , \qquad Y_{\bar{n}} = \varepsilon \cdot \Phi_n \cdot P_{n-\bar{n}} \cdot T_{mes}$$

$$\Rightarrow \qquad \tau_{n-\bar{n}} = \left(\frac{\varepsilon \cdot \Phi_n \cdot T_{mes.}}{Y_{\bar{n}}} \right)^{1/2} \cdot T_s$$

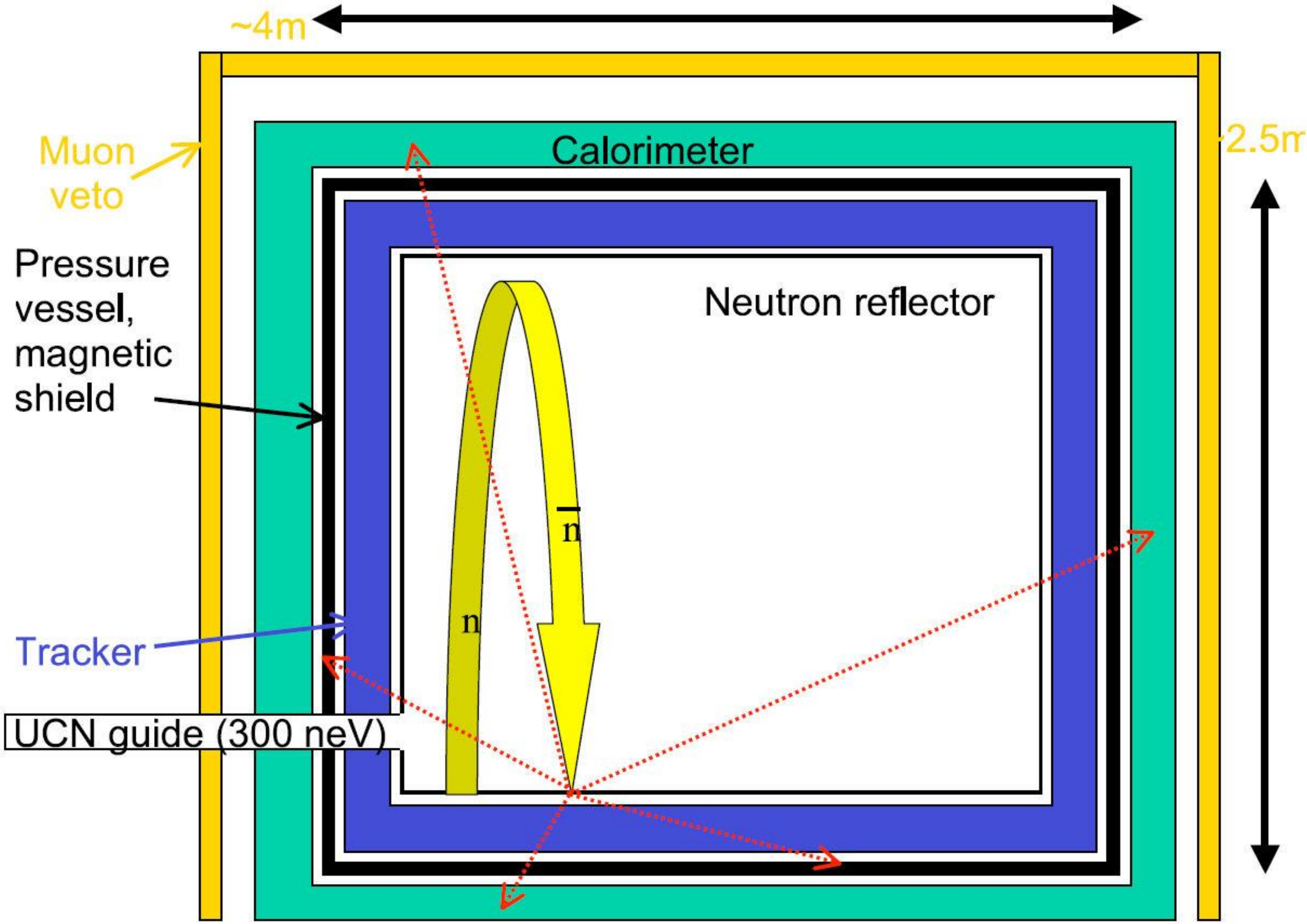
UCN beam intensity ; Φ_n = 10^8 n/sec

Storage time ; T_s = 500 sec

Detector efficiency ; ε = 0.5

Measurement time ; $T_{mes.}$ = 2×10^7 sec

➡ $\tau_{n\text{-}nbar}$ **~ 1.5 × 10^{10} sec** , however…



D.G. Phillips II et al., Phys. Rep. 612, 1-45 (2016)

Ultra Cold Neutron (cont.)

$$i\frac{\partial}{\partial t}\begin{pmatrix}\psi_n(t)\\ \psi_{\bar{n}}(t)\end{pmatrix}=\begin{pmatrix}E_n-i\Gamma_\beta/2+V(t) & \varepsilon\\ \varepsilon & E_n-i\Gamma_\beta/2+U(t)\end{pmatrix}\begin{pmatrix}\psi_n(t)\\ \psi_{\bar{n}}(t)\end{pmatrix}$$

For $\psi_n(0)=1,\ \psi_{\bar{n}}(0)=0,$

$$\left|\psi_{\bar{n}}(t)\right|^2=\frac{4\varepsilon^2}{\omega_W^2+4\varepsilon^2}\exp\left(-\Gamma_\beta t\right)\cdot\sin^2\left(\frac{1}{2}\sqrt{\omega_W^2+4\varepsilon^2}\,t\right)$$

where $\omega_W\equiv V(t)-U(t)=O\left(10^{-7}[\mathrm{eV}]\right)>>>\varepsilon<10^{-22}\ [\mathrm{eV}]$

($V(t)$ ($U(t)$) is (anti)neutron-wall potential)

Ultra Cold Neutron (cont.)

$$\text{For} \quad \psi_n(0) = 1, \ \psi_{\bar{n}}(0) = 0,$$

$$\left|\psi_{\bar{n}}(t)\right|^2 = \frac{4\varepsilon^2}{\omega_W^2 + 4\varepsilon^2} \exp\left(-\Gamma_\beta t\right) \cdot \sin^2\left(\frac{1}{2}\sqrt{\omega_W^2 + 4\varepsilon^2} t\right)$$

$$\rightarrow \ \left|\psi_{\bar{n}}(t)\right|^2 \cong \begin{cases} \varepsilon^2 t^2 & \left(\sqrt{\omega_W^2 + 4\varepsilon^2} t \ll 1\right) \\ \dfrac{4\varepsilon^2}{\omega_W^2 + 4\varepsilon^2} & \left(\sqrt{\omega_W^2 + 4\varepsilon^2} t \gg 1\right) \end{cases}$$

→ Antineutron amplitude is reset to zero on every reflection.

Ultra Cold Neutron (revised)

$$P_{n-\bar{n}} \approx \left(\frac{t_{TOF}}{\tau_{n-\bar{n}}} \right)^2 , \qquad Y_{\bar{n}} = \varepsilon \cdot \Phi_n \cdot P_{n-\bar{n}} \cdot T_{mes.} \cdot \frac{T_s}{t_{TOF}}$$

$$\Rightarrow \qquad \tau_{n-\bar{n}} = \left(\frac{\varepsilon \cdot \Phi_n \cdot \frac{T_s}{t_{TOF}} \cdot T_{mes.} \cdot t_{TOF}^2}{Y_{\bar{n}}} \right)^{1/2}$$

UCN beam intensity ; $\Phi_n = 10^8$ n/sec

Storage time ; $T_s = 500$ sec Flight time ; $t_{TOF} = 1$ sec

Detector efficiency ; $\varepsilon = 0.5$

Measurement time ; $T_{mes.} = 2 \times 10^7$ sec

➡ **$\tau_{n\text{-}nbar} \sim 7 \times 10^8$ sec**

Ultra Cold Neutron (cont.)

$$i\frac{\partial}{\partial t}\begin{pmatrix}\psi_n(t)\\ \psi_{\bar{n}}(t)\end{pmatrix}=\begin{pmatrix}E_n-i\Gamma_\beta/2-\boldsymbol{\mu}\cdot\mathbf{B}+V(t) & \varepsilon\\ \varepsilon & E_n-i\Gamma_\beta/2+\boldsymbol{\mu}\cdot\mathbf{B}+U(t)\end{pmatrix}\begin{pmatrix}\psi_n(t)\\ \psi_{\bar{n}}(t)\end{pmatrix}$$

For $\psi_n(0)=1,\ \psi_{\bar{n}}(0)=0,$

$$\left|\psi_{\bar{n}}(t)\right|^2=\frac{4\varepsilon^2}{\omega^2+4\varepsilon^2}\exp\left(-\Gamma_\beta t\right)\cdot\sin^2\left(\frac{1}{2}\sqrt{\omega^2+4\varepsilon^2}\,t\right)$$

where $\omega\equiv V(t)-U(t)-2\boldsymbol{\mu}\cdot\mathbf{B}$

$$\Rightarrow\quad \omega=0\quad\text{at}\ \ \mathbf{B}=\frac{V(t)-U(t)}{2\mu^2}\boldsymbol{\mu}$$

Summary

- Neutron-antineutron oscillation with $\tau_{\text{n-nbar}}=10^{6} \sim 10^{10}$ s is predicted by GUT having Left-Right symmetry and B-L symmetry in EW unification scale. $\Leftrightarrow m_{\nu,Majorana} \sim 100$ meV $\Leftrightarrow 0\nu\beta\beta$
- It is compatible with heavy right-handed neutrinos and suitable energy scale for seesaw mechanism.
- Planned experiment using VCN from with high flux reactor aims 10^{9} s.
- UCN with high efficiencies in production, storage, and detection can provide similar sensitivity.