The Phenomonology of Neutron-Antineutron Oscillations

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“Free” neutron oscillations (how free can they be?)

Neutron-antineutron oscillations in nuclei

Thanks for slides: Tony Mann, Yuri Kamyshkov, Ed Kearns,…

$n \leftrightarrow \bar{n}$ oscillations — can we add them to the list?

Neutral meson $|q\bar{q}\rangle$ states oscillate -

$$K^0, B^0 \longleftrightarrow \left[\text{2}^{\text{nd}}\text{ order weak}\right] \longleftrightarrow \overline{K^0}, \overline{B^0}$$

And neutral fermions can oscillate too -

$$\nu_\mu \longleftrightarrow \left[\ \cdots\ \right] \longleftrightarrow \nu_e$$

So why not -

$$n \longleftrightarrow \left[\text{New physics}\right] \longleftrightarrow \bar{n} \quad ?$$

Neutron is a long-lived neutral particle ($q_n<10^{-21}e$) and can oscillate into an antineutron. No oscillations have been seen yet.

Need interaction beyond the Standard Model that violates Baryon number (B) by 2 units. No experimental observation of B violation yet. But we expect B violation at some level

Neutron-Antineutron Oscillations: Formalism

$\alpha \neq 0$ allows oscillations

$$\Psi = \begin{pmatrix} n \\ \bar{n} \end{pmatrix}$$ n-nbar state vector

$$\mathrm{H} = \begin{pmatrix} E_n & \alpha \\ \alpha & E_{\bar{n}} \end{pmatrix}$$ Hamiltonian of n-nbar system

$$E_n = m_n + \frac{p^2}{2m_n} + U_n \quad ; \quad E_{\bar{n}} = m_{\bar{n}} + \frac{p^2}{2m_{\bar{n}}} + U_{\bar{n}}$$

Note :

- α real (assuming T)
- $m_n = m_{\bar{n}}$ (assuming CPT)
- $U_n \neq U_{\bar{n}}$ in matter and in external B [$\mu(\bar{n}) = -\mu(n)$ from CPT]

Neutron-Antineutron transition probability

For $H = \begin{pmatrix} E+V & \alpha \\ \alpha & E-V \end{pmatrix}$ $\qquad P_{n\to\bar{n}}(t) = \dfrac{\alpha^2}{\alpha^2+V^2} \times \sin^2\left[\dfrac{\sqrt{\alpha^2+V^2}}{\hbar} t\right]$

where V is the potential difference for neutron and anti-neutron.

Present limit on $\alpha \leq 10^{-23} eV$

Contributions to V:

<Vmatter> ~100 neV, proportional to matter density

<Vmag>=μB, ~60 neV/Tesla; B~10nT-> Vmag~10^{-15} eV

<Vmatter> , <Vmag> both >>α

For $\left[\dfrac{\sqrt{\alpha^2+V^2}}{\hbar} t\right] << 1$ ("quasifree condition") $\qquad P_{n\to\bar{n}} = \left(\dfrac{\alpha}{\hbar} \times t\right)^2 = \left(\dfrac{t}{\tau_{n\bar{n}}}\right)^2$

Figure of merit= NT^2 N=#neutrons, T="quasifree" observation time

Neutron-Antineutron oscillations: can I amplify the rate?

For $H = \begin{pmatrix} E+V & \alpha \\ \alpha & E-V \end{pmatrix}$ $\quad P_{n\to\bar{n}}(t) = \dfrac{\alpha^2}{\alpha^2+V^2} \times \sin^2\left[\dfrac{\sqrt{\alpha^2+V^2}}{\hbar}t\right]$

$$\text{mixing angle}: \tan\theta = \sqrt{1+(V/\alpha)^2} - (V/\alpha)$$

$$d\theta/dt << 2\sqrt{V^2+\alpha^2} \text{ adiabatic condition}$$

for level crossing

Unfortunately to meet this condition the neutron must spend an amount of time in a region with V<α which is many orders of magnitude longer than the neutron lifetime

Adiabatic level crossing can't help us

How to Search for N-Nbar Oscillations

Figure of merit for probability:

$$NT^2$$

N=total # of free neutrons observed

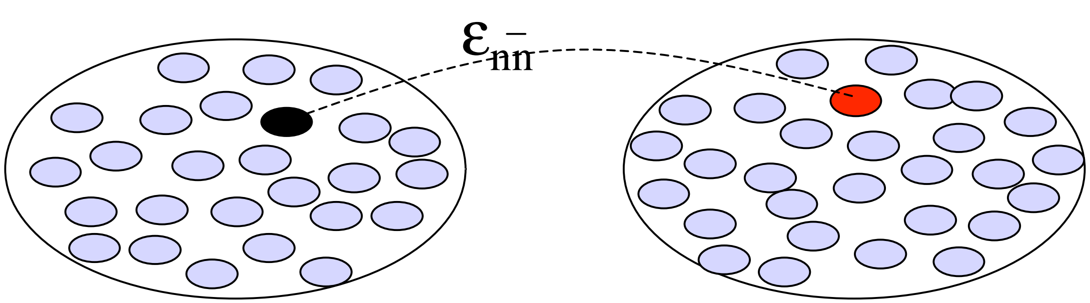
T= observation time per neutron while in “quasifree” condition

When neutrons are in matter or in nucleus, n-nbar potential difference is large->quasifree observation time is short

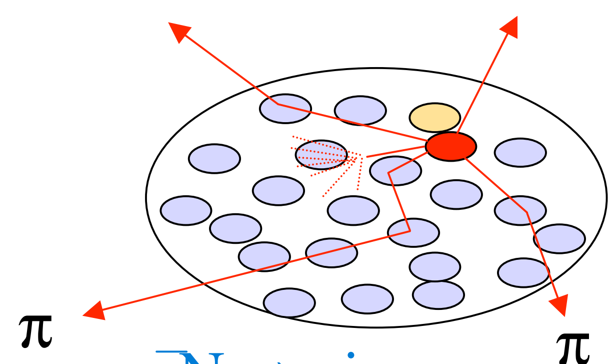
B field must be suppressed to maintain quasifree condition due to opposite magnetic moments for neutron and antineutron

(1) n-nbar transitions in nuclei in underground detectors

(2) Cold and Ultracold neutrons



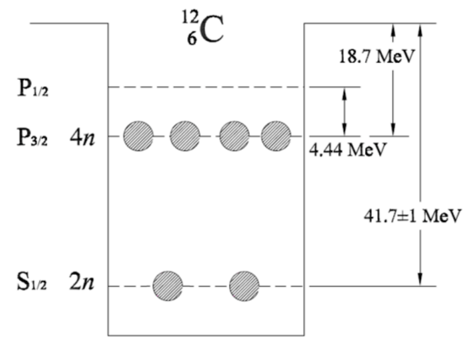
Nucleus A $\rightarrow$ A* + $\bar{n}$



$\bar{n}$N $\rightarrow$ pions

Suppression of n→nbar in intranuclear transitions

Neutrons inside nuclei are "free" for the time: $\Delta t \sim \dfrac{\hbar}{E_{binding}} \sim \dfrac{\hbar}{30MeV} \sim 4.5\times 10^{-22}s$



each oscillating with "free" probability $= \left(\dfrac{\Delta t}{\tau_{n\bar{n}}}\right)^2$

and "experiencing free condition" $N = \dfrac{1}{\Delta t}$ times per second.

Transition probability per second: $P_A \doteq \dfrac{1}{\tau_A} = \left(\dfrac{\Delta t}{\tau_{n\bar{n}}}\right)^2 \times \left(\dfrac{1}{\Delta t}\right)$

Intranuclear transition (exponential) lifetime: $\boxed{\tau_{\mathrm{A}} = \dfrac{\tau_{n\bar{n}}^2}{\Delta t} = R \leftrightarrow \tau_{n\bar{n}}^2}$

where $\mathrm{R} \sim \dfrac{1}{\Delta \mathrm{t}} \sim 4.5 \leftrightarrow 10^{22} s^{-1}$ is "nuclear suppression factor"

Actual nuclear theory suppression calculations for $^{16}O, ^{2}D, ^{56}Fe, ^{40}Ar$ by C. Dover et al; W.Alberico et al; B.Kopeliovich and J. Hufner, and most recently by Friedman and Gal (2008) corrected this rough estimate within a factor of 2

Vacuum N-Nbar transformation from bound neutrons:

Best result so far from Super-K in Oxygen-16

$$\boxed{\tau_{^{16}O} > 1.89 \leftrightarrow 10^{32}\, yr \quad (90\%\ \mathrm{CL})}$$

$\Re$ 24 observed candidates;
24.1 exp. background

$$\boxed{\tau_{nucl} \;=\; R \times \tau^{2}_{n\bar{n}\ \mathrm{free}}}$$

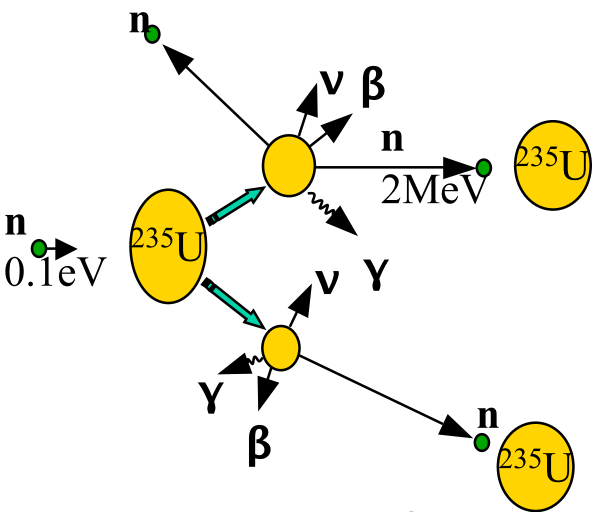
$$\text{if } R_{^{16}O} = 5 \cdot 10^{22}\, s^{-1} \quad \text{(from Friedman and Gal 2008)}$$

$$\Rightarrow \tau(\text{from bound}) > 3.5 \times 10^{8}\, s \quad \text{or} \quad \alpha < 2 \times 10^{-24}\, eV$$

$\leftrightarrow$16 times higher than sensitivity of ILL expt.

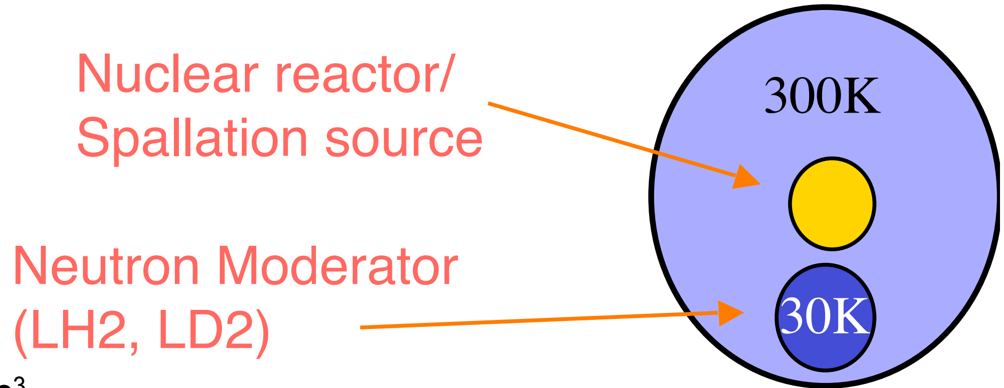
ILL limit (1994) for free neutrons: $\tau_{n\bar{n}} > 0.86 \times 10^{8}\, s$

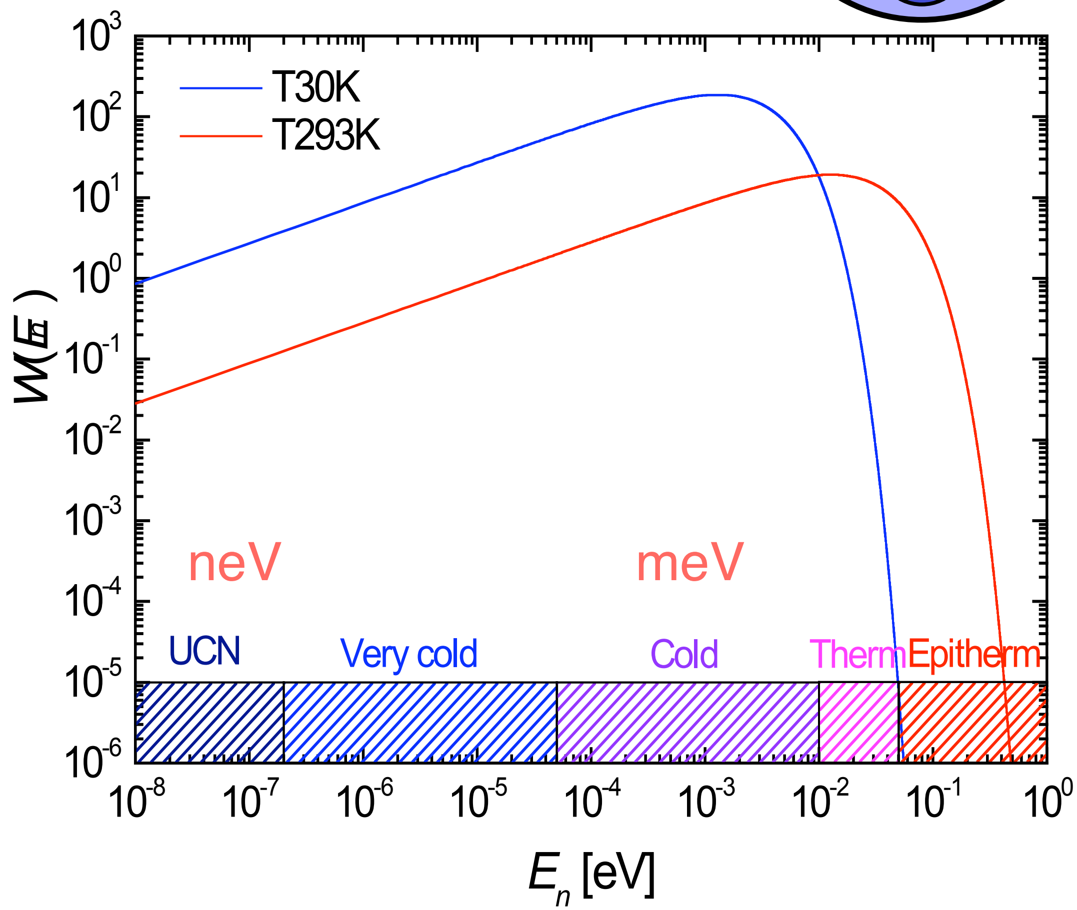
“Slow” Neutrons: MeV to neV



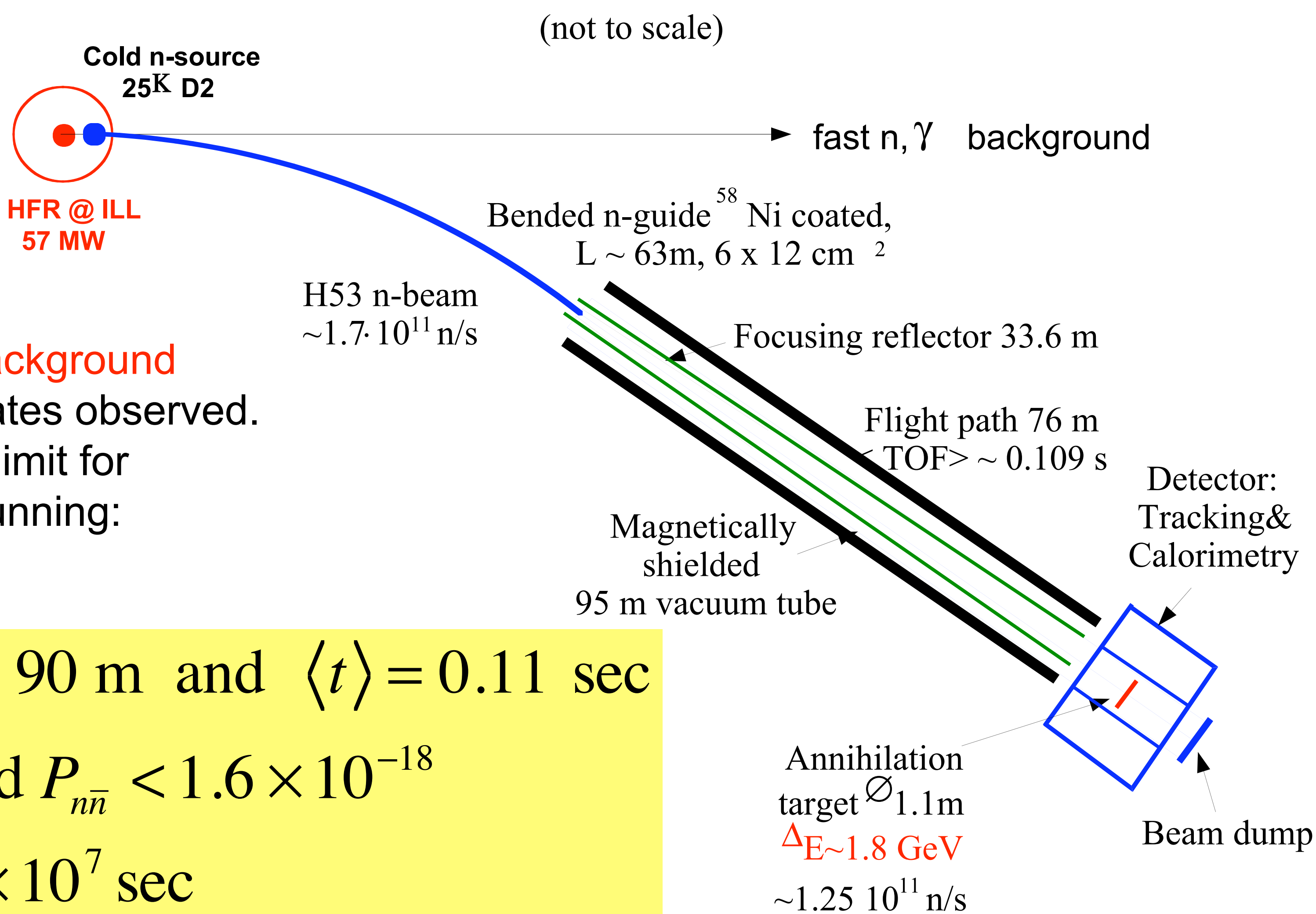
~MeV neutrons from fission or spallation, thermalized in ~ 20 collisions in ~ 100 μs

T (K)	E (meV)	λ (A)	v (m/sec)
300	25	1.6	2200
20	2	6.4	550





N-Nbar search at ILL (Heidelberg-ILL-Padova-Pavia)



No GeV background
No candidates observed.
Measured limit for
a year of running:

$$\text{with L} \sim 90\text{ m and } \langle t\rangle = 0.11\text{ sec}$$

$$\text{measured } P_{n\bar{n}} < 1.6\times10^{-18}$$

$$\tau > 8.6\times10^{7}\text{ sec}$$

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

Quasifree Condition: B Shielding and Vacuum

$\mu B t \ll \hbar$ ILL achieved |B|<10 nT over 1m diameter, 80 m beam,one layer 1mm shield in SS vacuum tank, 1% reduction in oscillation efficiency (Bitter et al, NIM A309, 521 (1991). For new experiment need |B|<~1 nT

If nnbar candidate signal seen, easy to "turn it off" by increasing B

$V_{opt} t \ll \hbar$:

Need vacuum to eliminate neutron-antineutron optical potential difference.

P<10^{-5} Pa is good enough, much less stringent than LIGO

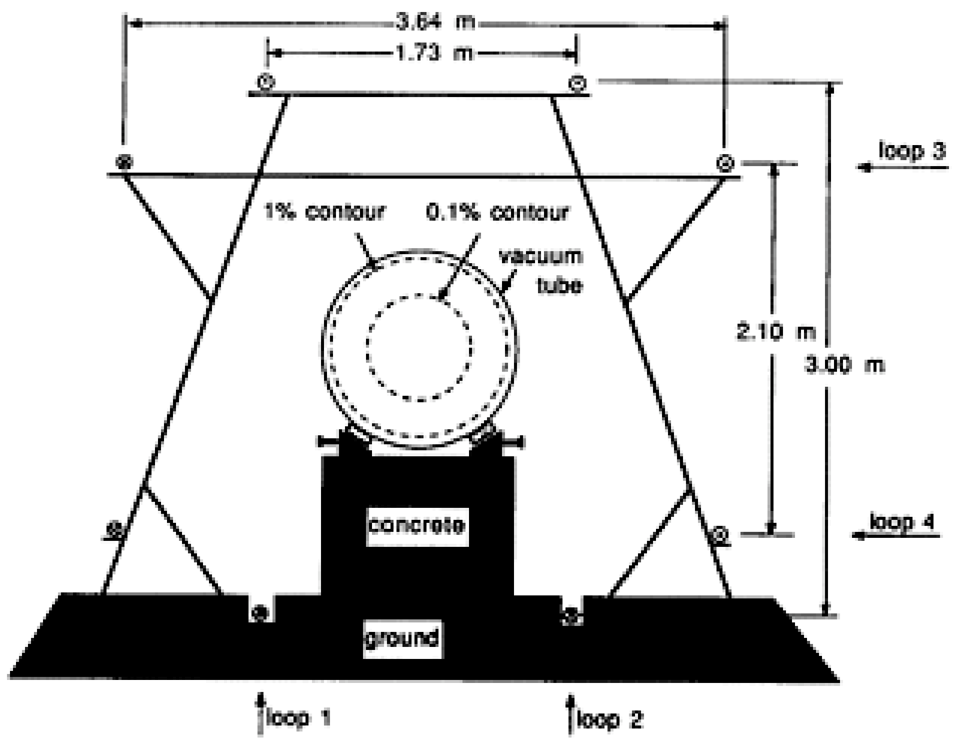
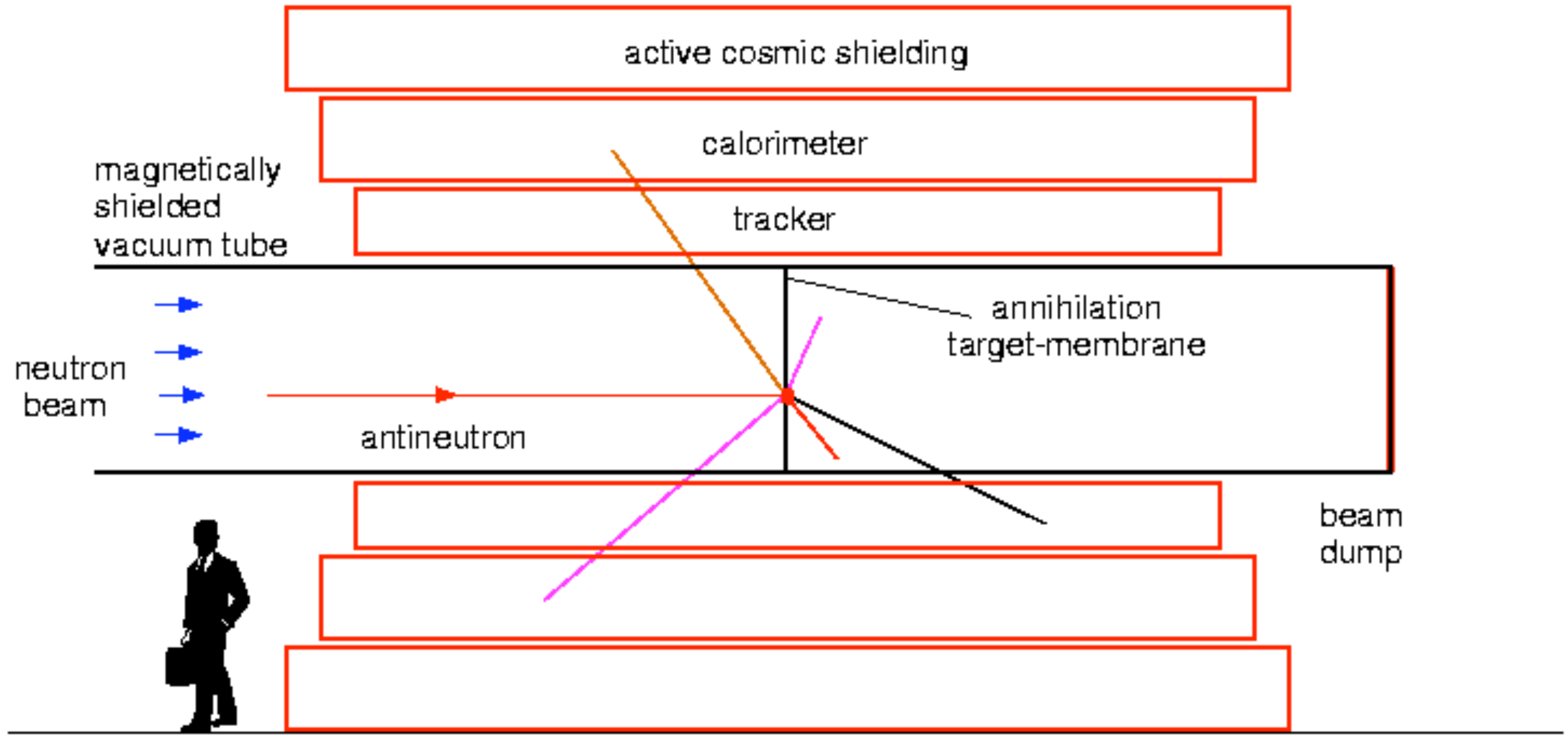


Fig. 10. The transverse field compensation system. Loops 1 and 2 are under 49 A current and compensate the horizontal field component; loops 3 and 4 are under 120 A current and compensate the vertical field component.

The conceptual scheme of antineutron detector



$$\boxed{\bar{n} + A \rightarrow \langle 5 \rangle \; pions \quad (1.8 \text{ GeV})}$$

Annihilation target: ~100μ thick Carbon film

$\sigma_{\text{annihilation}} \sim 4$ Kb $\qquad \sigma_{\text{nC capture}} \sim 4$ mb

vertex precisely defined. No background was observed

Summary

If we believe neutrons are electrically neutral, the only rule preventing them from oscillating is conservation of B. But there is no good reason to believe this, so we expect nnbar oscillations

The oscillation rate is greatly suppressed by matter or any nongravitational external fields unless observation time is short. Unlike the case of the MSW effect for neutrinos, it is impractical to amplify the rate using adiabatic level crossing

The present limits from free neutron experiments and from large underground detectors are the same order of magnitude. This is an insanely unlikely coincidence

If a nnbar candidate signal is seen in a free neutron experiment, it is easy to “turn it off” by increasing the external B, and a free beam allows one to sharply localize the nbar annihilation vertex