NNbar via sterile states of neutron – a new type of search

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He is feeling crook in his travel

His talk from his words is reproduced
by Yuri Kamyshkov. Any wrong statements
and errors are Y.K. faults

NEW $n \to \bar{n}$

Ordinary matter

Mirror matter

Old $\updownarrow$ mixing $\begin{pmatrix} n \\ \bar{n} \end{pmatrix}$

New $\leftarrow$ Mixing $\rightarrow$

$\begin{pmatrix} n' \\ \bar{n}' \end{pmatrix}$ Old $\updownarrow$ mixing

$n \leftrightarrow \bar{n}$

previously discussed

$n \leftrightarrow n'$

$n \leftrightarrow \bar{n}'$

$\bar{n} \leftrightarrow n'$

$\bar{n} \leftrightarrow \bar{n}'$

$n' \leftrightarrow \bar{n}'$

$$\boldsymbol{n} \equiv \begin{pmatrix} n \\ \bar{n} \\ n' \\ \bar{n}' \end{pmatrix} \text{ mixed – in components}$$

$$\boldsymbol{n}_{\text{initial}} \rightarrow \boldsymbol{n}_{\text{final}}$$

Final states

Initial states	n	$\bar{n}$	n'	$\bar{n}'$
n	1	ϵ	α	β
$\bar{n}$	ϵ	1	β	α
n'	α	β	1	ϵ
$\bar{n}'$	β	α	ϵ	1

4-component neutron mixing in measurements

$$\psi_n(t) = \begin{pmatrix} n \\ \bar{n} \\ n' \\ \bar{n}' \end{pmatrix} \qquad \psi_n(t=0) = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

$$i\hbar \frac{\partial}{\partial t} \begin{pmatrix} n \\ \bar{n} \\ n' \\ \bar{n}' \end{pmatrix} = \begin{pmatrix} E & \epsilon & \alpha & \beta \\ \epsilon & E & \beta & \alpha \\ \alpha & \beta & E & \epsilon' \\ \beta & \alpha & \epsilon' & E \end{pmatrix} \begin{pmatrix} n \\ \bar{n} \\ n' \\ \bar{n}' \end{pmatrix}$$

$$P_{n\to\bar{n}} = P(\epsilon, \alpha, \beta)$$

4 eigenvalues of energy

Some interesting details

- Parameter ϵ belongs to the OM world; the same way parameter ϵ' belongs to MM world, whereas α and β are responsible for exchange between OM and MM. So, ϵ–ϵ' and α–β corresponds to two different kinds of physics BSM.

- Hierarchy of magnitudes of α and β is not known. Naively one can think that $\alpha > \beta$. Berezhiani states that $\alpha = \beta$ is not possible. In the model, where Dark Matter is Mirror antimatter, it can be that $\beta > \alpha$. There are no good arguments that one is $\ll$ than another, e.g. can be as small as ϵ.

- Note, that in the first and second rows of matrix $\mathcal{H}_0$ α and β are assumed to be the same. That is according to the assumption that for α: $n \to n'$ = $\bar{n} \to \bar{n}'$ and for β: $n \to \bar{n}'$ = $\bar{n} \to n'$. That is kind of C-symmetry. In the rows 3 and 4 same α means: $n' \to n = \bar{n}' \to \bar{n}$; and same β: $\bar{n}' \to n = n' \to \bar{n}$ that are time inverted to the processes in rows 1 and 2.

- Another important note: complex mixing matrix $\mathcal{H}_0$ with 4×4 parameters should include several CP violating phases (assume Berezhiani will explore that).

State	$\Delta\mathcal{B} = \mathcal{B}_f - \mathcal{B}_i$	$\Delta\mathcal{B}'$	$\Delta(\mathcal{B} + \mathcal{B}')$	mixing
$n \to \bar{n}$	-2	0	-2	ϵ
$n \to n'$	-1	$+1$	0	α
$n \to \bar{n}'$	-1	-1	-2	β

$\uparrow\downarrow$

Starting with n, what can be observed in vacuum oscillations? Time evolution can be found by solving time dependent Schrödinger eq. with 4×4 Hamiltonian.

Final states (columns), Initial states (rows):

$\sim$	n	$\bar{n}$	n'	$\bar{n}'$
n	1	ϵ	α	β
$\bar{n}$	ϵ	1	β	α
n'	α	β	1	ϵ
$\bar{n}'$	β	α	ϵ	1

	If measured
$n \to n \to n$	$P \sim 1$
$n \to n \to \bar{n}$	$P \sim (1 \cdot \epsilon)^2$
$n \to \bar{n} \to \bar{n}$	$P \sim (\epsilon \cdot 1)^2$
$n \to n' \to \bar{n}$	$P \sim (\alpha \cdot \beta)^2$
$n \to \bar{n}' \to \bar{n}$	$P \sim (\beta \cdot \alpha)^2$

If final state is not measured, the system remains entangled. Oscillations continue.
After "measurement" given state can continue oscillations. Like 3 ν flavors.

$(|\alpha|^2 + |\beta|^2)$ measured by disappearance $n \to n', \bar{n}'$

Solution for probability $P_{n\to\bar{n}}$(t) with Hamiltonian $\mathcal{H}_0$ in vacuum will include direct transformation $n \to \bar{n}$ (through ϵ) and higher order free oscillations $n \to n' \to \bar{n}$ and $n \to \bar{n}' \to \bar{n}$ with total probability

$$P_{n\to\bar{n}}(t) = \frac{\epsilon^2 t^2}{\hbar^2} + \frac{2\alpha^2\beta^2 t^4}{\hbar^4}$$

Taking for example, limiting values for $\epsilon < 2.76 \times 10^{-24}\ eV$ (Super-K) and for disappearance (in some range of B: $\tau \gtrsim 10\ s$) $(\alpha^2 + \beta^2) < (6.6 \times 10^{-17})^2$, assuming also that $\beta/\alpha \approx$0.01, and probability is measured after 1 s of flight (from above formula):

$$P_{n\to\bar{n}}(t = 1\ s) \lesssim 10^{-17} + 10^{-8}$$

- $P_{n\to\bar{n}}(t) = P(\epsilon, \alpha, \beta)$
- Current limit for $P_{n\to\bar{n}}$ is usually assigned to ϵ only
- What if ϵ is very-very small, but α and β are large?
- $P_{n\to\bar{n}}(t) = P(0, \alpha, \beta) = P(\alpha, \beta)$
- What we call a "vacuum" for the absence of magnetic field $\boldsymbol{B}$, is not a vacuum for mirror magnetic field $\boldsymbol{B}'$
- For $n \to \bar{n}$ experiments performed in our "vacuum" 0-field the yield of $\bar{n}$ might be suppressed by mirror magnetic field.
- If large neutron – mirror neutron oscillations real, the existing ILL $n \to \bar{n}$ limit $\tau \geq 8.6 \times 10^7 s$ might mean nothing for process going through sterile states

$n \to \bar{n}$ via regeneration in resonance

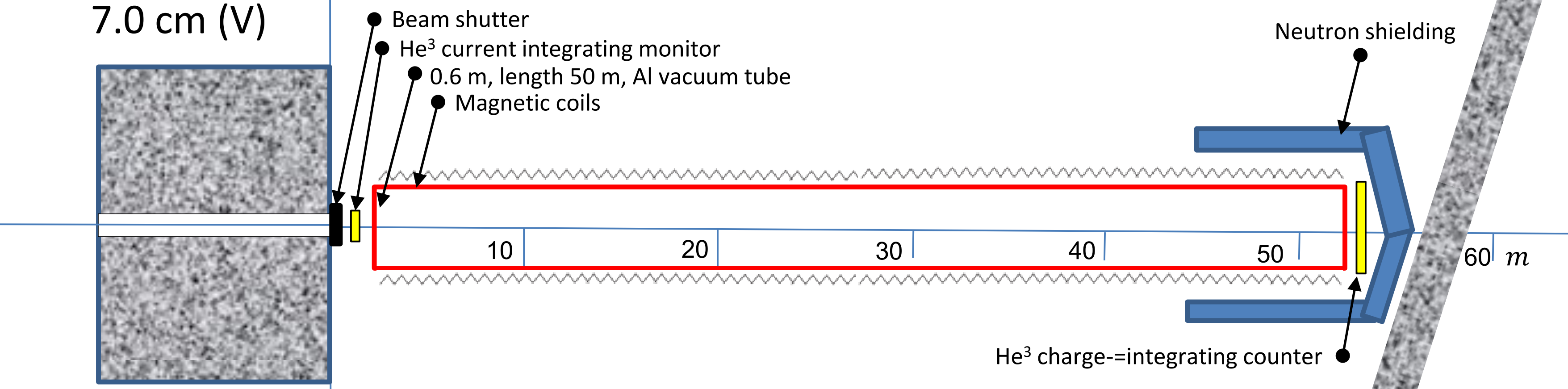
- Compensating $\boldsymbol{B}'$ by $\boldsymbol{B}$ we might see large yield of $\bar{n}$:
- First stage: disappearance $n \to n'$ or $\bar{n}'$ $(\alpha^2 + \beta^2)$ (assuming direct $n \to \bar{n}$ is small $\epsilon = 0$) to establish that effect can happen with measured sensitivity for given $\boldsymbol{B}' = \boldsymbol{B}$

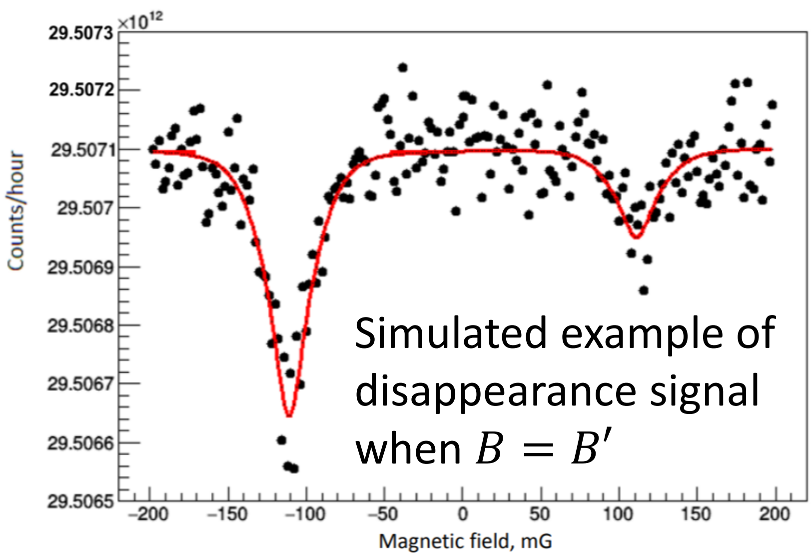
- Second stage experiment: Absorption of the remaining neutron beam, then in mag. field
- Regeneration $n' \to \bar{n}$ (β^2) and $\bar{n}' \to \bar{n}$ (α^2)
- Total probability $2\,\alpha^2\,\beta^2$ in the resonance when $|B' - B| = 0$

HIBEAM Experiment Layout at ESS for n disappearance measurement (2023-2027)

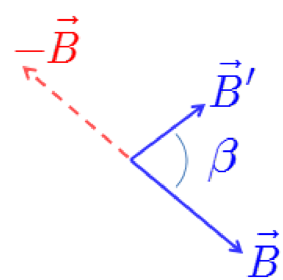
22m

beam hole:
11.2 cm (H)
7.0 cm (V)

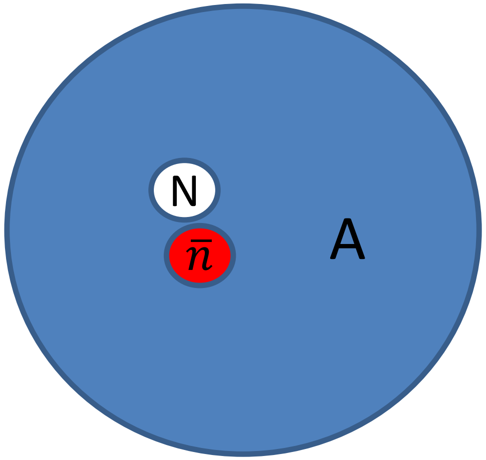




intensity through dia 1 m @ 54 m is 6.4E+10 n/s
ESS @ 1 MW



What happens inside nuclei?



OLD $n \to \bar{n}$ in nuclei:

$$n \to \bar{n} \qquad \sim\epsilon^2$$

$$\bar{n} + N \to < 5 > \pi$$

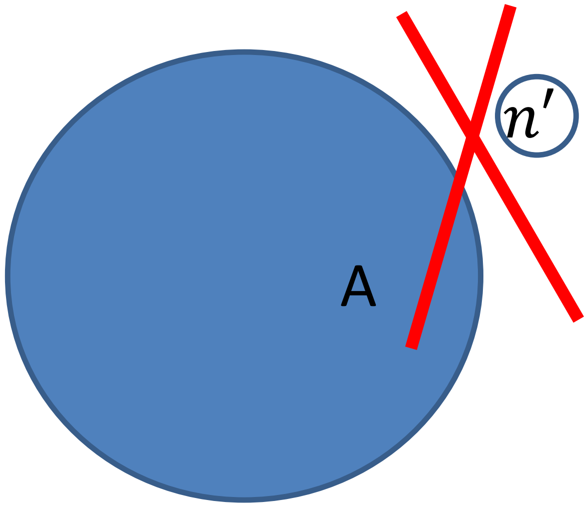
Intranuclear suppression:

$$\tau_A = R\tau_{n\to\bar{n}}^2 = R\frac{1}{\epsilon^2}$$

suppression factor $R = R_A \cong 5 \times 10^{22} s^{-1}$

From $\tau_A = 1.9 \times 10^{32} yrs$ Super-K experiment extracted $\tau_{n\to\bar{n}}$>$2.7 \times 10^8\ s$

NEW $n \to n'$ and $n \to \bar{n}$ in nuclei



$$n \to n' \qquad \sim\alpha^2$$

It is impossible inside nuclei due to energy conservation

Second order (like $2\beta 0\nu$) process possible:

$n_1 \to \bar{n}'$; $n_2 \to n'$; $\bar{n}' + n' \to$ <5> π'

but will have oscillation time $\tau \sim R^2 \frac{1}{2\alpha^2\beta^2}$

Some Conclusions

It is possible to consider, as not excluded scenario, if neutron to mirror neutron transformations exist, then

- $\epsilon \cong 0$, no direct $\Delta\mathcal{B} = 2$ transformations exist, but
- $n \rightarrow \bar{n}$ might happen through oscillations to mirror world states
- it can be seen as $2\,\alpha^2\,\beta^2$ if $\boldsymbol{B} \neq \boldsymbol{B}'$ suppression is removed in the beam of neutrons (like in NNbar experiment).
- it can be seen also in regeneration as $2\,\alpha^2\,\beta^2$ producing pure $\bar{n}$
- Then the $n \rightarrow \bar{n}$ through sterile states might be not observable in previously though NNbar experiment with $B = 0$, also will not be seen in intranuclear process.
- It seems that this simple experiment should be tried before big NNbar.