A new experimental approach to search for free neutron-antineutron oscillations, based on coherent neutron and antineutron mirror reflection

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Neutron-antineutron oscillations

$$n - \bar{n} \qquad\qquad \Delta B = 2$$

An **observation** of neutron-antineutron oscillations, which violate both Baryon and Baryon-Lepton conservation, would constitute a scientific discovery of fundamental importance to **physics and cosmology**.

A stringent **upper bound** on its transition rate would make an important contribution to our understanding of the Baryon asymmetry of the universe by eliminating the **post-sphaleron baryogenesis** scenario in the light quark sector.

Two methods used in the past

$(t\Delta E/\hbar)^2 < 1$

1. $n-\bar{n}$ oscillations in the so-called **quasi-free** limit with no suppression by external fields (magnetic fields, residual gases, wall reflection etc), thus oscillation probability is proportional to the **square of the observation time**);

2. $n-\bar{n}$ oscillations **in nuclei** (much larger number of neutrons available but much shorter observation times because of the suppression of oscillations by strong nuclei fields).

$$\begin{pmatrix} |n_1\rangle \\ |n_1\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} |n\rangle \\ |\bar{n}\rangle \end{pmatrix}$$

with

$$\tan(2\theta) = \frac{2\varepsilon}{(2\vec{\mu}_n \cdot \vec{B} - V_n + V_{\bar{n}})}.$$

Two methods used in the past

In any case, the **appearance of antineutrons** would be the signature of this process.

At present, both methods provide comparable constraints for the characteristic oscillation time equal to **~10^8 sec** (nuclei constraints are better but model-dependent).

We propose a **new method**, which combines somehow advantages of the two methods (**the knowledge of nuclear suppression** of oscillations and (quasi)-**model-free interpretation** of results) and can provide an improvement in the sensitivity of **4 orders of magnitude** in terms of the oscillation probability.

The new concept

A development of the quasi-free-neutron method: **cold neutrons** are allowed to **bounce** from the neutron guide walls. An antineutron would travel along the same trajectory, without annihilating and/or loosing coherence of the two states, for **extended periods of time**.

Analogy to the proposed earlier experiments with **ultracold neutrons** [M.V. Kazarnovski et al, JETP Lett. 32 (1980) 82; K.G. Chetyrkin et al, Phys. Lett. B 99 (1981) 358; H. Yoshiki, R. Golub, Nucl. Phys. A 501 (1989) 869] but those proposals did not consider coherence of neutrons and antineutrons at reflection, or did not identified conditions at which coherence is maintained.

The new concept

We:

- Extend this approach to **higher neutron energies**, thus largely increasing statistics and experiment sensitivity,
- Point out conditions for suppressing the **phase difference** for neutrons and antineutrons at reflection,
- Underline the importance of setting **low transverse momenta** of neutrons,
- and making **certain choices for the nuclei** composing the guide material.

Advantages of the new concept

For **the same installation length**, advantages include

- **Smaller transversal sizes**,
- **Lower costs**,
- **Larger statistics** (higher accuracy) (one can use VCNs).

For **a larger length**,

the **gain in sensitivity**, in terms of the oscillation probability, increases quadratically with length (and still a large reductions of costs).

Advantages of the new concept

Our proposal is based on:

1. Standard quantum mechanics (mainly),

and

2. Some knowledge of antineutron-nuclei scattering lengths (this is important to a smaller extend, especially for short observation times)

Crucial parameters of the problem

Crucial **parameters** for the analysis of this problem are:

- The probability of neutron and antineutron reflection per wall collision, $\boldsymbol{\rho_n}$ and $\boldsymbol{\rho_{\bar{n}}}$,
- The difference of phase shifts of the wave function per wall collision, $\boldsymbol{\Delta\varphi_{n\bar{n}} = \varphi_n - \varphi_{\bar{n}}}$.

They depend on:

- The optical potential for neutrons $\boldsymbol{U_n = V_n + iW_n}$, and
- The optical potential for antineutrons $\boldsymbol{U_{\bar{n}} = V_{\bar{n}} + iW_{\bar{n}}}$.

Optimal conditions

In order to optimize the **sensitivity** of neutron-antineutron searches and simultaneously to decrease the **impact** of theoretical uncertainties, we will use the following limit:

$e \ll V_n$, $e \ll V_{\bar{n}}$, $e \sim W_{\bar{n}}$, $W_n \ll V_n$, $W_{\bar{n}} \ll V_{\bar{n}}$, $W_n \ll W_{\bar{n}}$, with e the energy of transversal neutron motion. Then, for the probabilities: $\rho_n = 1$ and $1 - \rho_{\bar{n}} \approx \frac{2kk''_{\bar{n}}}{(k'_{\bar{n}})^2}$, with $k'_{\bar{n}} \approx \sqrt{2mV_{\bar{n}}}$ and $k''_{\bar{n}} \approx \sqrt{m\left(\frac{W_{\bar{n}}^2}{2V_{\bar{n}}}\right)}$ and for the phase shift: $\Delta\varphi_{n\bar{n}} \approx \frac{2k}{k_n k'_{\bar{n}}}(k_n - k'_{\bar{n}})$

Decreasing perpendicular velocities

Imagine two upstream sections a two-dimensional ballistic neutron guide (with a cross-section increasing from ***h*** by ***d*** to ***H*** by ***D***). Typical cross-sections are ***hd*** ~10² cm², ***HD*** ~10⁴ cm², respectively. In according with Liouville theorem, tangential velocity components would decrease from $\sim 2v_{crit}^{Ni}$ to $|v_{hor}| < 2v_{crit}^{Ni}\frac{d}{D}$ and $|v_{vert}| < \sqrt[3]{4hv_{crit}^{Ni}g}$.

Antineutron-nuclei scattering lengths

$$b_{\bar{n}A} \sim 1.54\sqrt[3]{A} - i$$

Element	$b_{\bar{n}A}$ [fm]	$U_{\bar{n}}$ [neV]	$\tau_{\bar{n}}$ [s]
C	$3.5 - i$	$103 - i29$	1.7
Mg	$3.5 - i$	$39 - i11$	1.0
Si	$3.7 - i$	$48 - i13$	1.2
Ni	$4.7 - i$	$111 - i24$	2.3
Cu	$4.7 - i$	$104 - i22$	2.2
Zr	$5.3 - i$	$59 - i11$	1.8
Mo	$5.3 - i$	$89 - i16$	2.3
W	$6.5 - i$	$106 - i16$	3.0
Pb	$6.7 - i$	$57 - i8.6$	2.3
Bi	$6.7 - i$	$49 - i7$	2.1

Phase-shift times (W184+186)

Then, $\tau_{hor}^{\Delta\varphi,\bar{n}} = \frac{D}{\overline{|v_{hor}|}} \cdot \frac{\sqrt{V_n V_{\bar{n}}}}{2\sqrt{\overline{e_{hor}}}\left(\sqrt{V_n}-\sqrt{V_{\bar{n}}}\right)} \sim 32\ s$ and

$$\tau_{vert}^{\Delta\varphi,\bar{n}} = \frac{\overline{|v_{vert}|}}{g} \frac{\sqrt{V_n V_{\bar{n}}}}{\sqrt{\overline{e_{vert}}}\left(\sqrt{V_n}-\sqrt{V_{\bar{n}}}\right)} \sim 7.3\ s$$

Note, however, that a factor $\left(\left(\sqrt{V_n} - \sqrt{V_{\bar{n}}}\right) \rightarrow 0\right)$ can allow to largely increase these characteristic times by proper mixing of two isotopes/elements for the guide wall material if needed.

Annihilation times (W184+186)

$$\tau_{hor}^{\rho,\overline{n}} = \frac{D}{\overline{\overline{|v_{hor}|}}} \frac{(V_n)^{3/2}}{W_{\overline{n}}\sqrt{\overline{\overline{e_{hor}}}}} \sim 15\ s,$$

$$\tau_{vert}^{\rho,\overline{n}} = \frac{2\overline{|v_{vert}|}}{g} \frac{(V_n)^{3/2}}{W_{\overline{n}}\sqrt{\overline{\overline{e_{vert}}}}} \sim 3.1\ s.$$

$\tau_{vert}^{\rho,\overline{n}}$ is THE real limitation of this method.

Even in the limit of "zero" vertical velocities, this estimation will not significantly change.

You can improve this value by using a "**parabolic**" neutron guide but not much.

Statistical sensitivity in some cases

- A **small-scale** experiment: **PF1B** facility at ILL: neutron flux of 10^10 n/cm2/s, guide cross section 6x20 cm2, flight length 65 m, annihilation detector active area 0.5 x 0.5 m2, experiment duration 1 year: an improvement of **$>10^1$** over the best existing limit;
- A **middle-scale** experiment: future **ESS cold neutron** guide, flight length 200-300m: an improvement of **$\sim 10^3$** over the best existing limit;
- An **optimized experiment**, in particular using a dedicated source of VCNs or a large guide length would bring an improvement of **$>10^4$** over the best existing limit.

Systematical uncertainties

An uncertainty can be associated with the fact that the interaction of slow antineutrons with nuclei has not been measured, and **theoretical** models contain **uncertainties**.

-for **PF1B**, the time of flight is 0.05 s, much shorter than antineutron storage times of a few seconds, thus this uncertainty is **negligible** even with very poor knowledge of antineutron-nuclei scattering lengths,

-for **ESS**, the time of flight is 0.4 s, $\tau_{\bar{n}}/\tau_{\rm obs} \sim 5.$ $\Delta {\rm Im} b_{\bar{n}A}/{\rm Im} b_{\bar{n}A} = \Delta {\rm Im} a_{\bar{n}A}/{\rm Im} a_{\bar{n}A} \sim 0.1$ and the systematic error in estimating the oscillation time is as small as **0.5%**.

- For an experiment with **long observation time** and optimized statistical sensitivity, the systematic uncertainty would increase and **should be studied** in each case.

Possible nearest actions

- Neutronic calculations and optimizations (neutron production, extraction, softer spectrum? broader transverse velocities?);
- Antineutronic calculations and optimization (using theoretically estimated antineutron scattering lengths);
- Experimental measurements of antiproton scattering lengths for the selected nuclei(isotopes) for the neutron/antineutron guide;
- "Fine tuning" of parameters of the system and conservative estimations of the sensitivity. An experiment at PF1B might be the closest and simplest goal.