A new experimental approach to search for free neutron-antineutron oscillations, based on coherent neutron and antineutron mirror reflection from the walls of a neutron/antineutron guide

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This talk is based on several recent articles

- V.V.N.,V.G.,K.V.P.,W.M.S.,A.Y.V., "*Experimental approach to search for free neutron-antineutron oscillations based on coherent neutron and antineutron mirror reflection*", **Phys. Rev. Lett.** 122 (2019) 221802; "*A new operating mode in experiments searching for free neutron-antineutron oscillations based on coherent neutron and antineutron mirror reflections*", **Eur. Phys. J. Web Conf.** 191 (2018) 01005;
- V.V.N.,V.G.,K.V.P.,W.M.S.,A.Y.V., "Comment on B.O. Kerbikov "The effect of collisions with the wall on neutron-antineutron transitions" Phys. Lett. B 795 (2019) 362", **Phys. Lett. B** 803 (2020) 135357
- V.G.,V.V.N.,K.V.P.,W.M.S.,A.Y.V., "*A new approach to search for free neutron-antineutron oscillations using coherent neutron propagation in gas*", **Phys. Lett. B** 808 (2020) 135636
- K.V.P.,V.G.,E.A.K.,V.V.N.,W.M.S.,A.Y.V., "*Theoretical analysis of antineutron-nucleus data needed for antineutron mirrors in neutron-antineutron oscillation experiments*", **Phys. Rev. D** 102 (2020) 075025
- D.M., V.V.N., K.V.P., V.S., M.W.S., et al, "*A possible neutron-antineutron oscillation experiment at PF1B*", **Symmetry**, to be submitted (2021)

Neutron-antineutron oscillations

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

An **observation** of neutron-antineutron oscillations, which violate both Baryon and Baryon-Lepton conservation, would constitute an important discovery for **physics and cosmology**.

A stringent **upper bound** on its transition rate would also 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

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

1. $n-\bar{n}$ oscillations in the so-called **quasi-free** limit with no suppression by external fields (magnetic fields, residual gases, wall reflections etc), thus oscillation probability is proportional to the **square of the observation time**);
2. $n-\bar{n}$ oscillations **in nuclei** (a much larger number of neutrons is available but much shorter observation times are allowed 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).

The weaknesses of the two existing methods:

- **Lower statistical** sensitivity, for free neutron oscillations,
- **Larger systematics**, for large-scale low-background detectors

Our proposal

We propose a **new method**, which combines the advantages of the two methods:

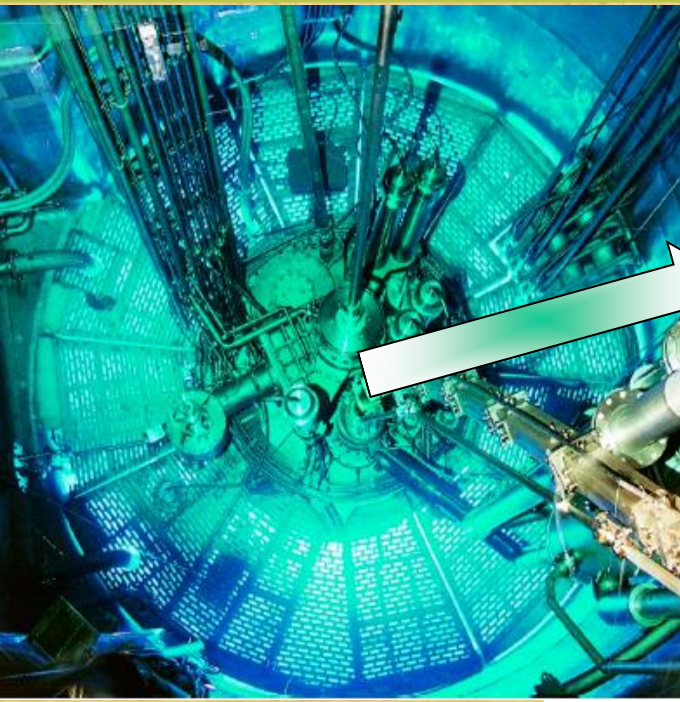
- **the knowledge of nuclear suppression** of oscillations and
- the (quasi)-**model-free interpretation** of results

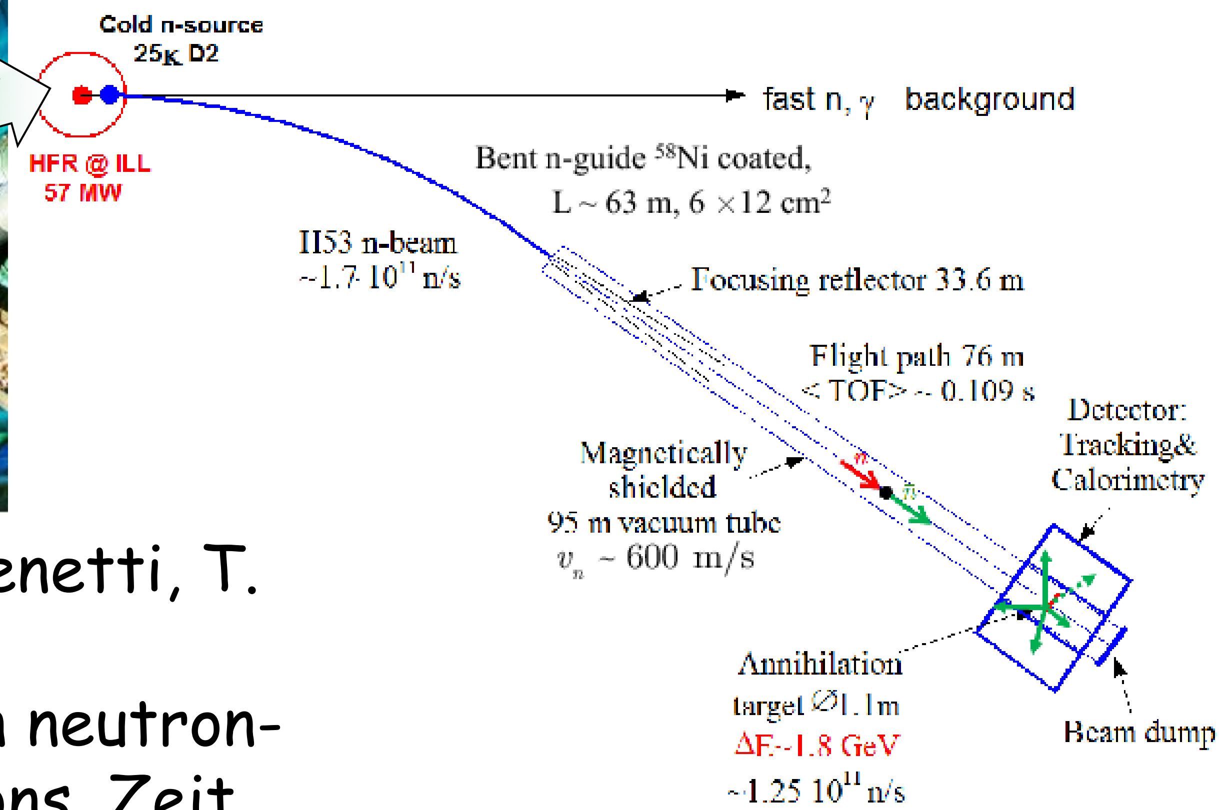
It improves simultaneously:

- **Statistical** sensitivity compared to free neutron oscillations,
- **Systematics** compared to large-scale low-background detectors

It can provide an improvement in the sensitivity of up to **4 orders of magnitude** in terms of the oscillation probability.

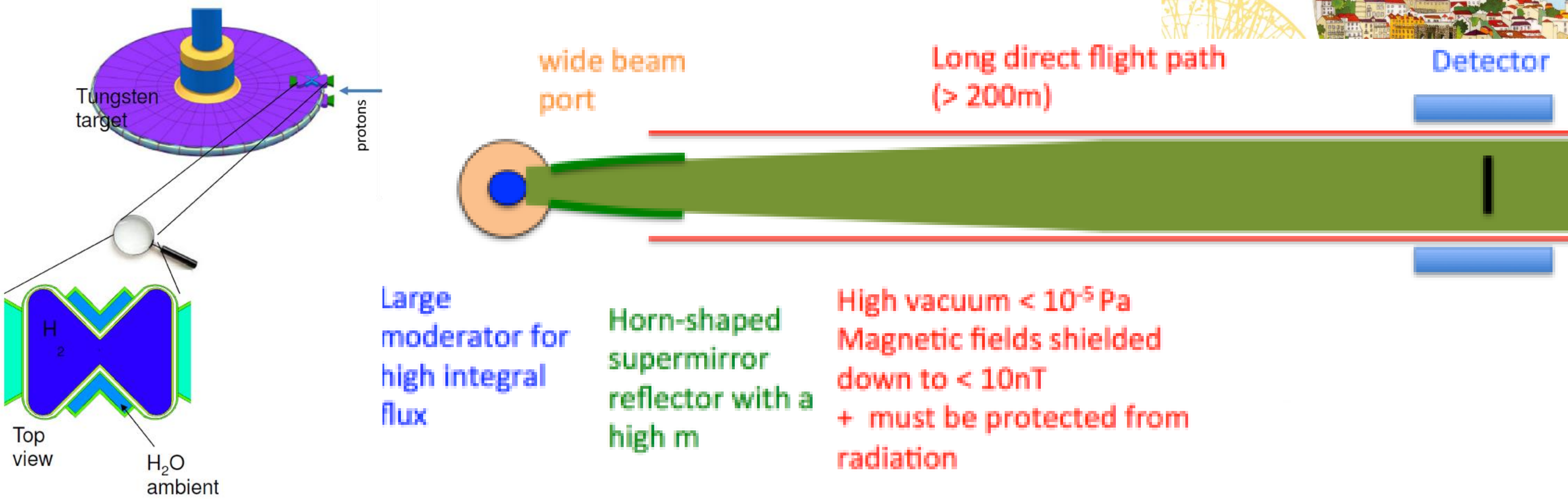
The best performed experiment





M. Baldo-Ceolin, P. Benetti, T. Bitter, et al. A new experimental limit on neutron-antineutron oscillations. Zeit. Phys. C 63 (1994) 409.

The best planned experiment



ESS: European Spallation Source. One of largest projects with the budget of about 2 Milliards euros. NNbar is the largest experiment currently considered at ESS (USA-Europe collaboration with over 50 main participants from over 20 universities/institutes. Extensive improvement of parameters of the previous experiment. An expected gain of 2-3 orders of magnitude.

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 the 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** (an experiment becomes feasible),
- **Significantly lower costs** (an experiment becomes feasible),
- **Significantly larger statistics** (higher accuracy) (one can also use very cold neutrons (VCNs) if there is a dedicated VCN source).

For **a larger length** :

- A large **gain in sensitivity**, in terms of the oscillation probability, which increases quadratically with length (and still a large reductions of costs compared to a shorter "standard" experiment).

Advantages of the new concept

Our proposal is based on:

1. Standard quantum mechanics (simply reflection of a particle from a potential step; even if the parameters of this reflection potential are known with significant uncertainties, the probability of a sub-barrier reflection is anyway close to 100% and can be predicted with small absolute uncertainties),

and

2. Some knowledge of antineutron-nuclei scattering lengths (this is important to a smaller extend, especially for short observation times as nearly all antineutrons would reach the annihilation detector anyway)

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 are defined by:

- 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

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In order to optimize the **sensitivity** of neutron-antineutron searches and simultaneously to decrease the **impact** of theoretical uncertainties, we will use the following **natural** limit (a “gift of nature”):

$e \ll V_n$, $e \ll V_{\bar{n}}$, $e \sim W_{\bar{n}}$, $W_n \ll V_n$, $W_{\bar{n}} \ll V_{\bar{n}}$, $W_n \ll W_{\bar{n}}$, 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 the upstream section of a ballistic neutron guide with a cross-section increasing from $h \times d$ to $H \times D$). Typical cross-sections are hd~10^2 cm^2, HD~10^4 cm^2, 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

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

Both the annihilation of neutrons and the phase shift at reflection are defined by the interaction of antineutrons with the bottom wall of the guide (the velocity is smaller at the top wall due to gravity, the velocity at side walls can be decreased to any value simply by adiabatically extending the horizontal size of the guide)

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

Statistical sensitivity in some cases

- A **small-scale** experiment: **PF1B** facility at ILL: neutron flux ~10^{10} n/cm^2/s, guide cross section 6x20 cm^2, flight length 65 m, annihilation detector active area 0.5x0.5 m^2, experiment duration 1 year: an improvement of **>10^1** over the best existing limit;
- A **middle-scale** experiment: future **ESS cold neutron** guide with similar flux, flight length 200-300 m, broad spectrum of transversal velocities, longer measuring time: an improvement of **~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, and the systematic error in estimating the oscillation time is ~**0.5%**.

$$\Delta \mathrm{Im} b_{\bar{n}A}/\mathrm{Im} b_{\bar{n}A} = \Delta \mathrm{Im} a_{\bar{n}A}/\mathrm{Im} a_{\bar{n}A} \sim 0.1$$

$$\tau_{\bar{n}}/\tau_{\mathrm{obs}} \sim 5.$$

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

Nearest actions

- Neutronic calculations and optimizations (neutron production, extraction, a softer spectrum (VCNs)? broader initial transverse velocities?);

- Antineutronic calculations and optimizations (using theoretically estimated antineutron scattering lengths, an optimized shape and material of the neutron/antineutron guide, an optimized antineutron annihilation detector);

- An experiment at PF1B at ILL with a gain factor of >10 might be the closest and simplest goal.