Is it possible to design a high-sensitivity search for neutron-antineutron oscillations at the new UCN/VCN source in Kazakhstan?

- The "clock-non-reset" method,
- Advantages of the new UCN/VCN source in Kazakhstan and the sensitivity estimations,
- Requirements for the infrastructure needed.

This talk is based on the following publications:

- V.V. N., V. Gudkov, K.V. Protasov, W.M. Snow, A.Yu. Voronin, "*Experimental approach to search for free neutron-antineutron oscillations based on coherent neutron and anti-neutron mirror reflection*", **Phys. Rev. Lett. 122** (2019) 221801;
- V.V. N., V. Gudkov, K.V. Protasov, W.M. Snow, A.Yu. Voronin, "*Comment on B.O. Kerbikov "The effect of collisions with the wall on neutron-antineutron transitions*", **Phys. Lett. B 803** (2020) 135357;
- V.V. N., V. Gudkov, E. Kupryanova, K. Protasov, M. Snow, A. Voronin, "*Implementation of neutron/antineutron guides in experiments searching for n-nbar oscillations*", **PANIC2021** (2021) 42B;
- V.V. N., "*Why very cold neutrons could be useful for neutron-antineutron oscillation searches*", **J. Neutron Res. 24** (2022) 223.

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 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

1. $n - \bar{n}$ oscillations of neutrons in the so-called **quasi-free** limit, when oscillations are not suppressed by external fields (magnetic field, optical potential of residual gases, *etc*), and thus the probability of oscillations is proportional to the **square of the observation time** (time intervals shorter than ~$\Delta E / \hbar$);
2. $n - \bar{n}$ oscillations of neutrons **bound in nuclei** (much larger number of neutrons available but much shorter observation times because of the suppression of oscillations by strong nuclei fields).

Two methods used in the past

In any case, the **appearance of antineutrons** is the signature of the process.

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

We proposed a **new method**, which combines somehow the advantages of the two methods (**the knowledge of nuclear suppression** of oscillations and (quasi)-**model-free interpretation** of results) and provides a great improvement in the sensitivity (compared to the best existing result).

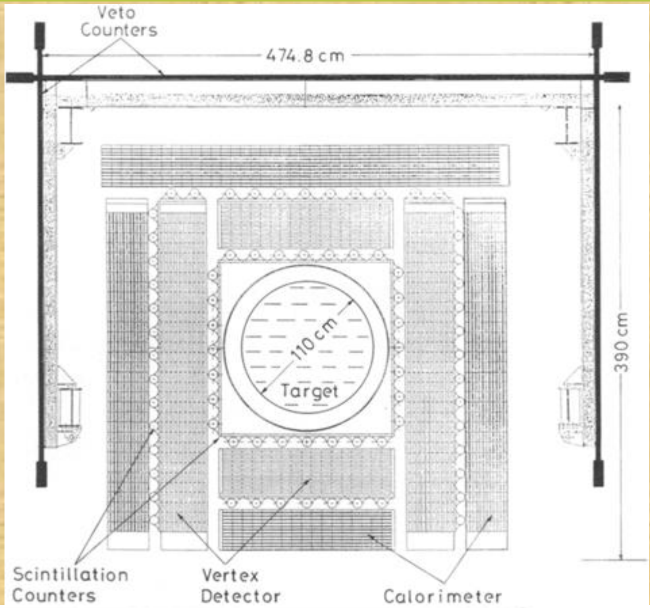
The best existing results

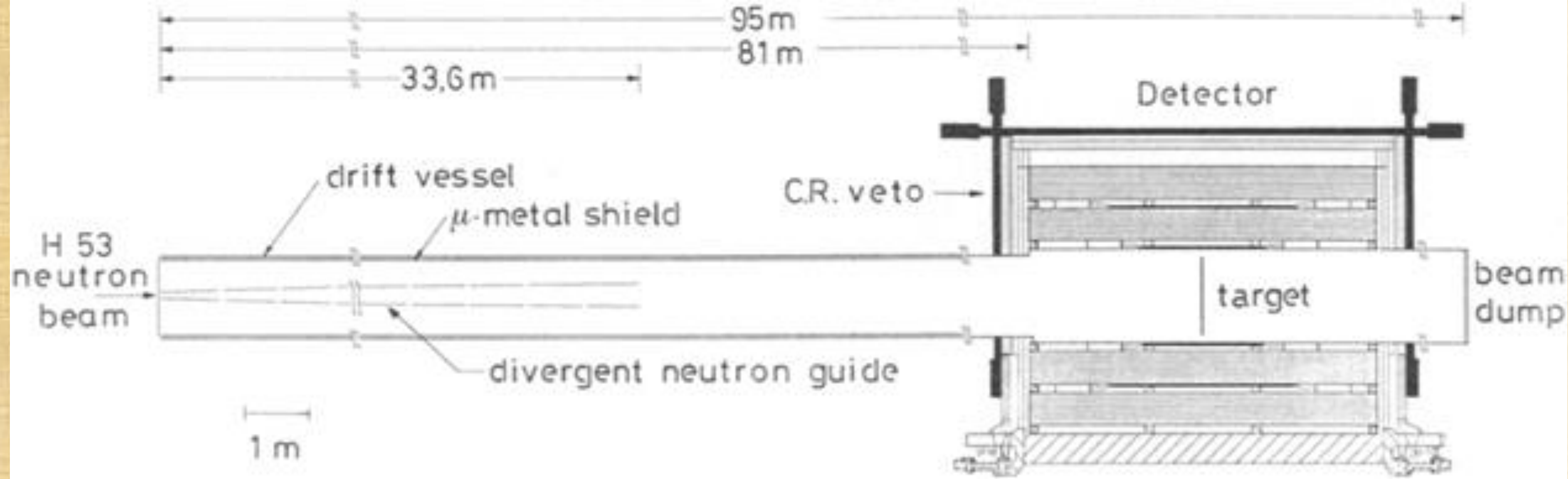
M. Baldo-Ceolin, et al, "*A new experimental limit on neutron-antineutron oscillations*", **Z. Phys. C 63** (1994) 409

$\boldsymbol{\tau_{n\bar{n}} > 0.86 \cdot 10^{8} s}$

Parameters of this experiment:

$F_n \sim 10^{11} s^{-1}$; $\tau \sim 0.1 s$; $T \sim 2.4 \cdot 10^{7} s$





The new concept

Development of the quasi-free-neutron method: **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 an **extended period 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 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**, include

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

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 justified by:

1. (mainly) The validity of quantum mechanics [E. Fermi, *Sul moto dei neutroni nelle sostanze idrogenate*, **Ric. Sci. 7** (**1936**) 13.] - the effective optical potential (Fermi potential) is introduced in precisely the same way for neutrons and antineutrons, and
2. (to a smaller extend) some knowledge of antineutron-nuclei scattering lengths [K.V. Protasov, V. Gudkov, E.A. Kupryanova, V.V. N., W.M. Snow, A.Y. Voronin, "*Theoretical analysis of antineutron-nucleus data needed for antineutron mirrors in neutron-antineutron oscillation experiments*", **Phys. Rev. D 102** (**2020**) 075025]

Estimation of the oscillation probability

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$P_{n\to\bar{n}} \approx \varepsilon^2 e^{-\frac{\Gamma_a}{2}t} t^2$: The **probability** of neutron-antineutron oscillation depends essentially only on a few parameters: ε, the neutron-antineutron **mixing** parameter, Γ_a, the antineutron annihilation **width**, and time t.

For the optimum observation time $t = \frac{4}{\Gamma_a}$ (obtained by differentiation of the formula above), the probability is: $P_{n\to\bar{n}} \approx 2.1\left(\frac{\varepsilon}{\Gamma_a}\right)^2$ (the optimum is not sharp, and there is only one parameter left).

Crucial parameters of the problem

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

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

They depend on:

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

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: $\Delta\varphi_{n\bar{n}} \approx \frac{2k}{k_n k'_{\bar{n}}}(k_n - k'_{\bar{n}})$

Horizontal geometry

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 ~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 $|v_{vert}| < \sqrt[3]{4hv_{crit}^{Ni}g}$.

Examples

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

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

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

Characteristic annihilation times (W184+186)

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

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

$\tau_{vert}^{\rho,\bar{n}}$ 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 vertical extraction of neutrons, then nearly no constraints on the observation time !

Sensitivity estimations

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M. Baldo-Ceolin, et al, "*A new experimental limit on neutron-antineutron oscillations*", **Z. Phys. C 63** (1994) 409

$$\boldsymbol{\tau_{n\bar{n}} > 0.86 \cdot 10^8 s}$$

Parameters of this experiment: $F_n \sim 10^{11} s^{-1}$; $\tau \sim 0.1 s$; $T \sim 2.4 \cdot 10^7 s$

INP Kazakhstan:

VCN phase-space density 3-5 $\Downarrow$, VCN velocity 20 $\Downarrow$, thus, $F_n \sim 10^9 s^{-1}$

$\tau \sim 3.0 s$; $T \sim 2.2 \cdot 10^8 s$

Thus, the gain factor is **~80**

Sensitivity estimations

Additional gain factors to be discussed:

- With an advanced VCN extraction system, **~10-20**

- With the vertical neutron guide of **~100 m**, an additional gain factor of **~10**

Requirements for the infrastructure

- A VCN source (for instance, a helium VCN source surrounded by a layer of fluorinated nanodiamonds, probably it might be combined with the UCN source),
- An extraction system which provides the largest extracted VCN flux (simplified by the geometry of the thermal column),
- A horizontal VCN guide with the length of 200-400 m (is there sufficient space available around the reactor ?),
- Long measuring time ~10 years (would the reactor still be running?),
- A significant budget (an international collaboration?).