Experiments on the vertical neutron channel

- Neutron-antineutron oscillations

and briefly mention

- Small-angle scattering of VCN
- Spin-echo with VCN?

A new method to detect neutron-antineutron oscillations

[V.V. N., V. Gudkov, K.V. Protasov, W.M. Snow, A.Yu. Voronin, *A new operating mode in experiments searching for free neutron-antineutron oscillations based on coherent neutron and antineutron mirror reflections*, ArXiv:1810.04988/hep-ex (2018)]

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Neutron-antineutron oscillations

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

An **observation** of neutron-antineutron oscillations, which violate both Barion and Barion-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).

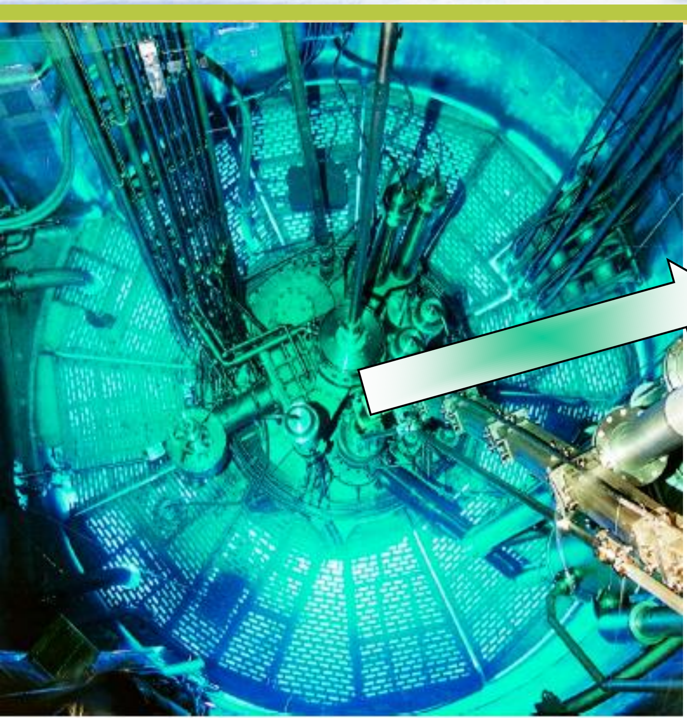
Two methods used in the past

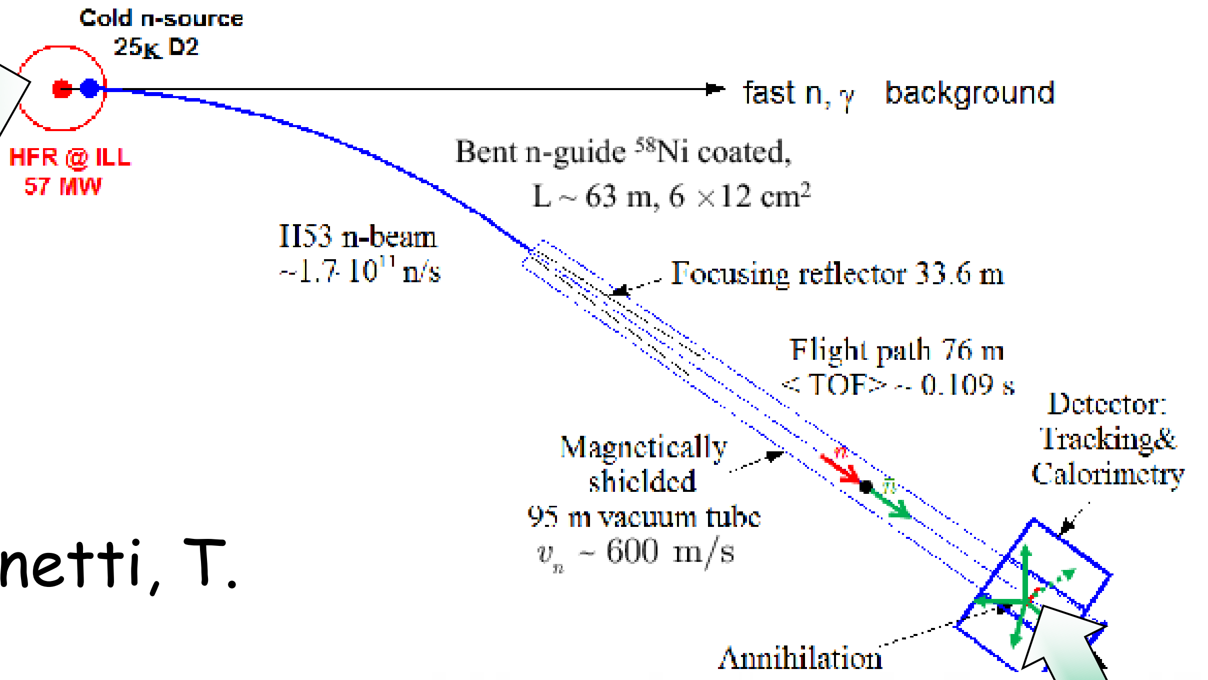
In any case, the **appearance of antineutrons** is the signature of the process.

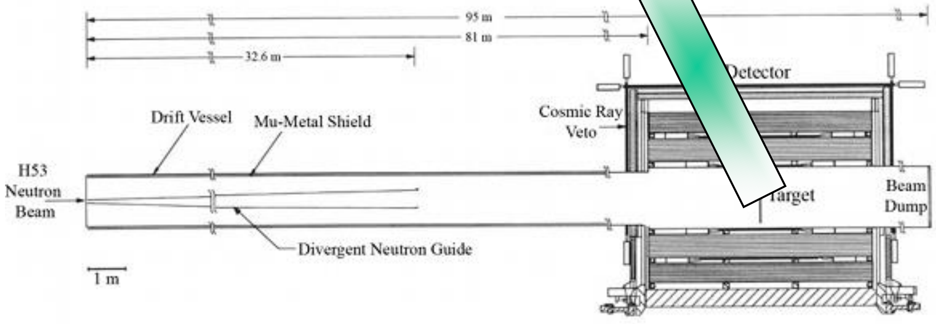
At present, both methods provide comparable constraints for the characteristic oscillation time equal to **~10^8 sec** (nuclei constraints are slightly better but model-dependent).

We propose 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 provide an improvement in the sensitivity of **4 orders of magnitude** in terms of the oscillation probability.

The best constrain with free neutrons

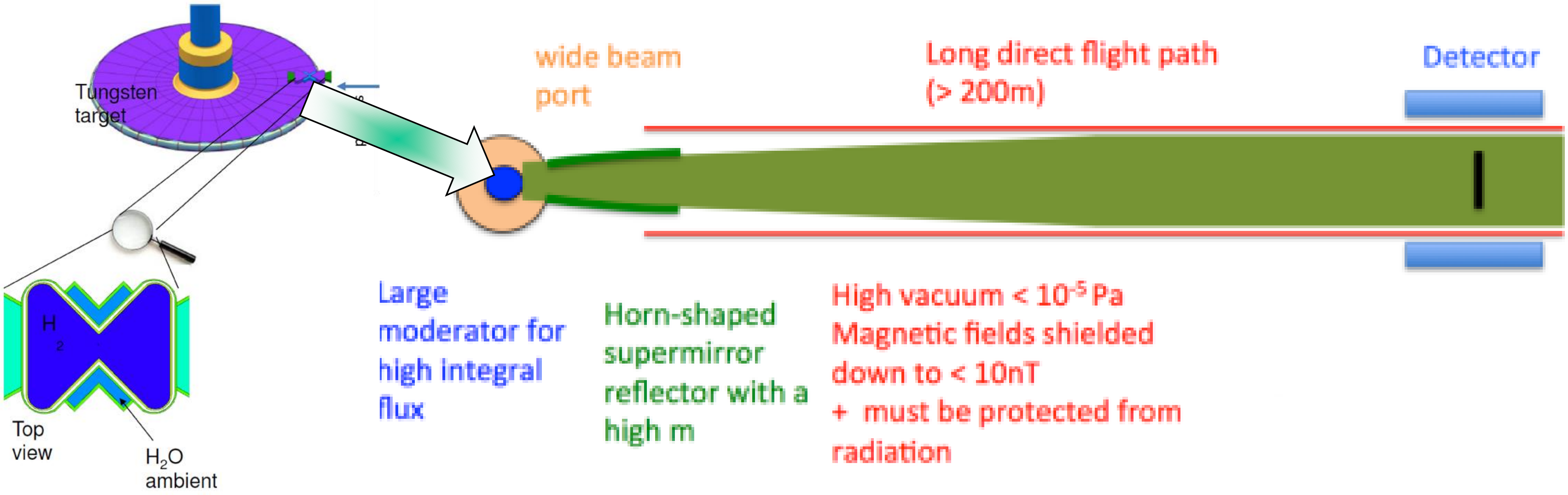






M. Baldo-Ceolin, P. Benetti, T. Bitter, et al. A new experimental limit on neutron-antineutron oscillations. Zeit. Phys. C 63 (1994) 409.

A new experiment proposed at ESS



Large moderator for high integral flux

Horn-shaped supermirror reflector with a high m

High vacuum < 10^{-5} Pa
Magnetic fields shielded down to < 10nT
+ must be protected from radiation

ESS: European Spallation Source.$n - \bar{n}$ 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 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].

The new concept

We:

- Extend this approach to **higher neutron energies**,
- 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).

For **a larger length**,

the **gain in sensitivity** of up to **~10^4 over** the existing PF1/ILL result in terms of the oscillation probability could be achieved

Estimation of the oscillation probability

$P_{n\to\bar{n}} \approx \varepsilon^2 e^{-\frac{\Gamma_a}{2}t} t^2$: 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:

$$P_{n\to\bar{n}} \approx 2.1\left(\frac{\varepsilon}{\Gamma_a}\right)^2$$

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:

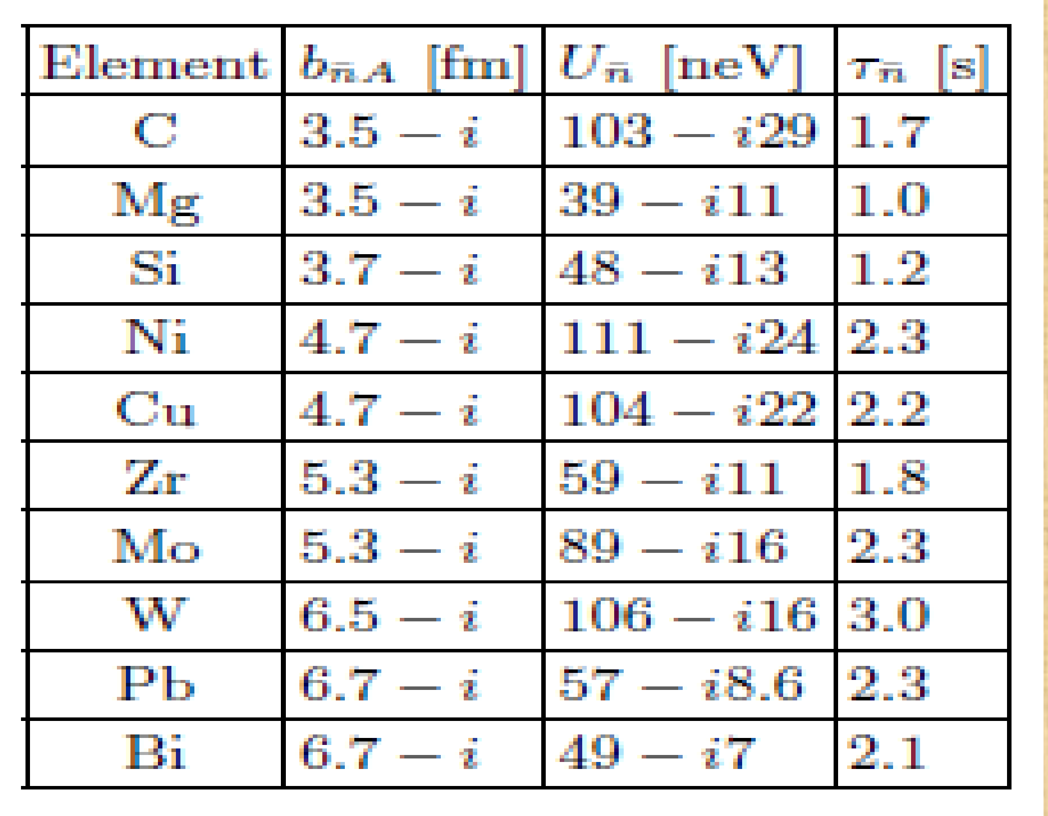
$e \ll V_n, e \ll V_{\bar{n}}, e \sim W_{\bar{n}}, W_n \ll V_n, W_{\bar{n}} \ll V_{\bar{n}}, W_n \ll W_{\bar{n}}$, with e the energy of transversal neutron motion. Then, for the probabilities: $\rho_n = 1$ and $1 - \rho_{\bar{n}} \approx \frac{2kk''_{\bar{n}}}{(k'_{\bar{n}})^2}$, with $k'_{\bar{n}} \approx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

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

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

$\tau_{vert}^{\rho,\bar{n}}$ 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 "**parabolic**" neutron guide.

Sensitivity estimations

A 1-year measurement with an installation of an "optimum length" at a cold neutron beam with PF1B or PIK, or ESS neutron intensity would bring an improvement of **~10^4** over the existing PF1 result.

But, the "optimum length" is ~700[m/s]*3sec*2 ~4km (the optimum is not sharp, thus the length can be reduced).

- Any project has to **optimize** the gain/cost ratio.
- One could always start from a "**short**" version with already record sensitivity and then update the experiment.

A possible alternative: a vertical fountain

Very Cold Neutrons (VCNs): large effect of gravity -> vertical extraction (upwards to multiply the factor of merit by 4 (the height is somewhere between Jet d'eau de Geneve (140m) and Samson fountain in Peterhof (20m))

Two good news:

- "Ideal" neutron guide, NO effect of annihilation and dephasing;
- Fluorinated nano-diamond reflectors.

Raising height, velocity and time-of-flight

52.9 m/s ; 10.6 s

37.4 m/s ; 7.5 s

26.5 m/s ; 5.3 s

0 m/s ; 0 s

The raising height versus the initial neutron velocity and the time-of-flight

For a large-area dedicated VCN source, a realistic gain factor over the PF1 result is ~3*10^3.