This talk is based on an unpublished paper:

Tentatively: A new concept for experiments searching for neutron-antineutron oscillations,

$n-\bar{n}$

$\Delta B = 2$

by

V.V. N., V. Gudkov, K.V. Protasov,

M.W. Snow, and A.Yu. Voronin

A 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 extended period of time, thus increasing sensitivity quadratically (about 4 orders of magnitude).

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

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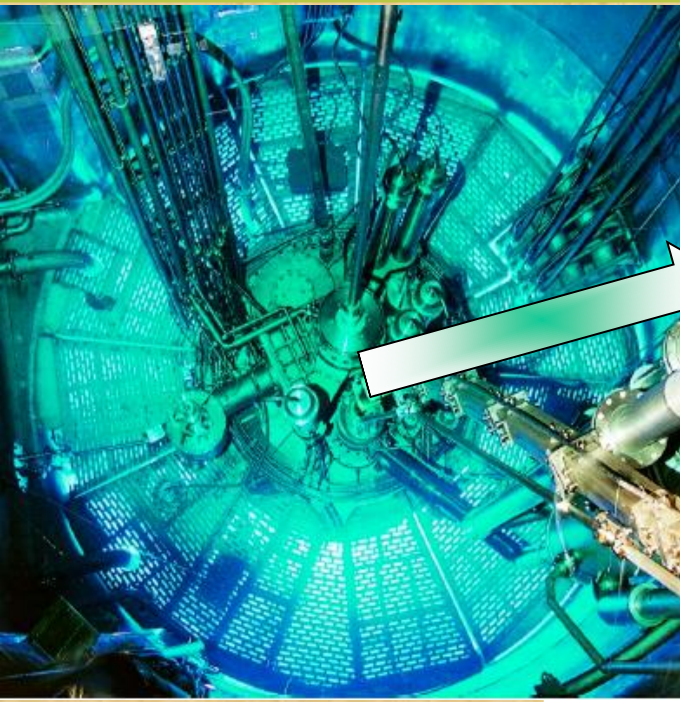
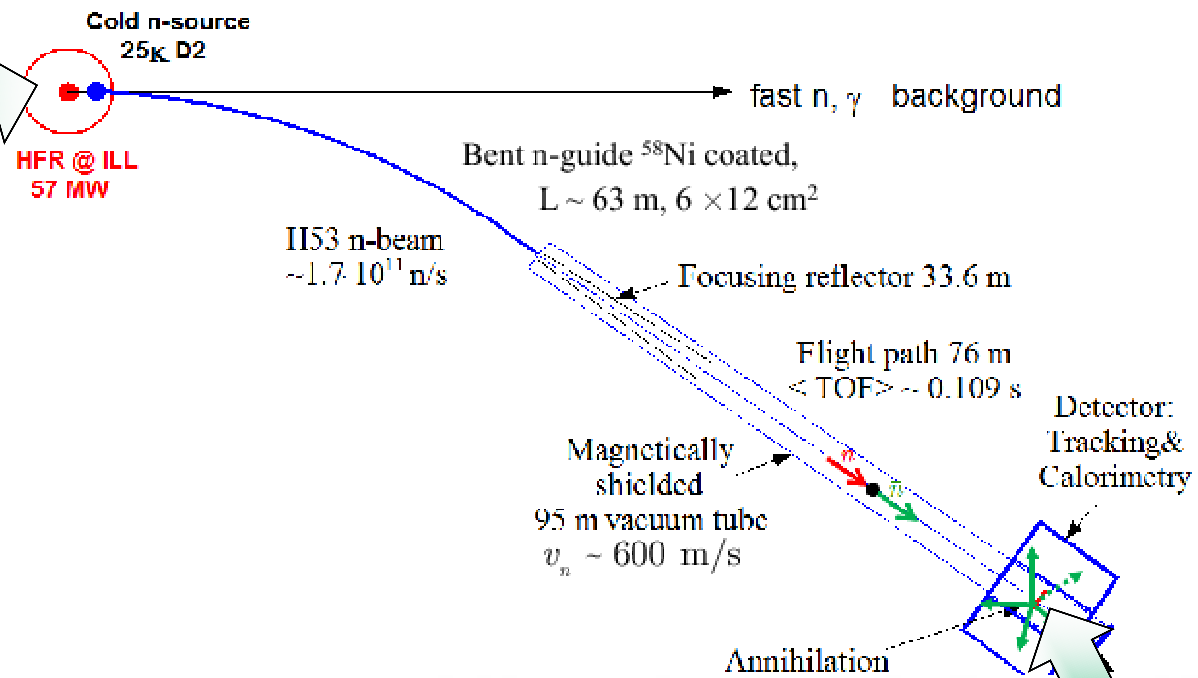
In any case, the appearance of antineutrons is the signature of the process.

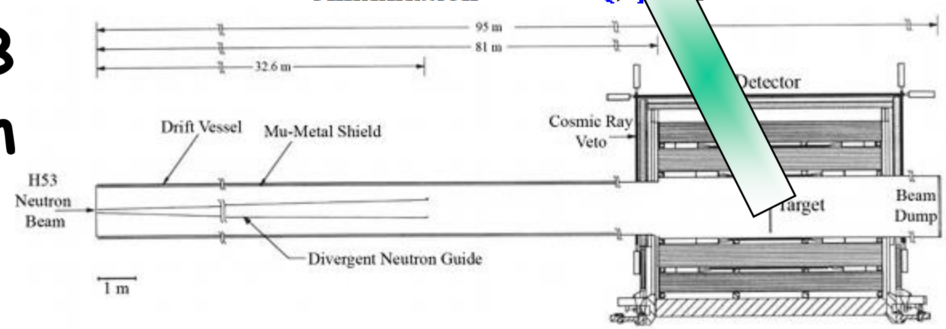
At present, both methods provide comparable constraints for the characteristic oscillation time equal to ~10^8 sec (nuclei constraints are slightly better but model-dependent).

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

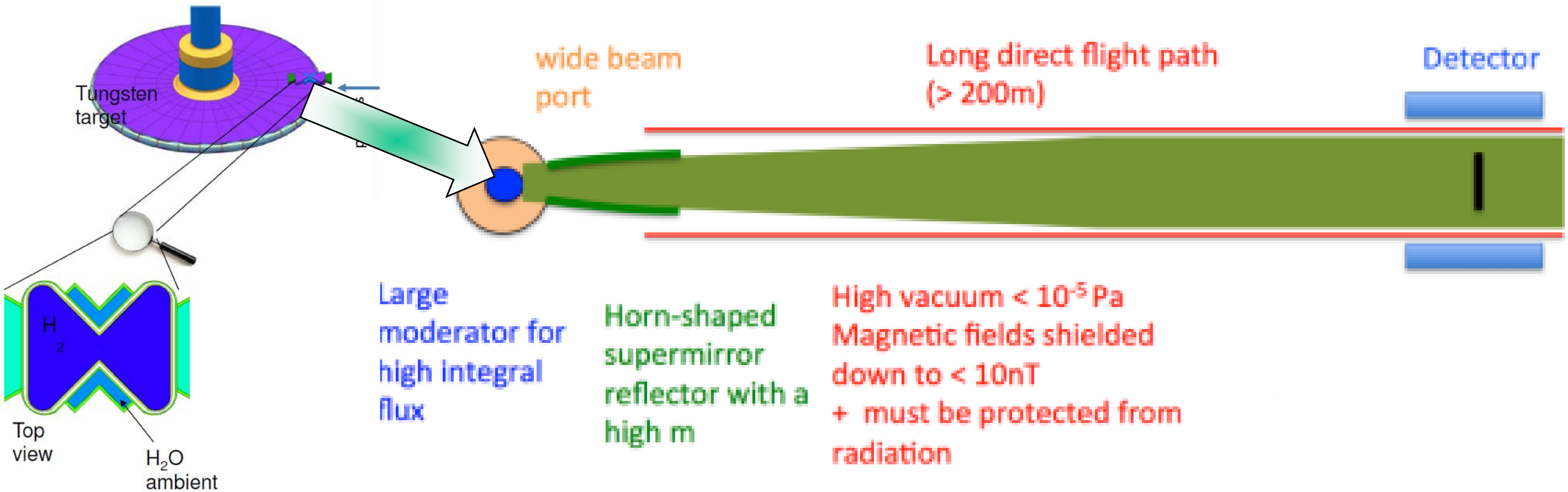






M. Baldo-Ceolin, P. Benetti, T. B et al. A new experimental lim neutron-antineutron oscillations. Phys. C 63 (1994) 409.

A new experiment proposed at ESS



ESS: European Spallation Source. One of largest projects with the budget of about 2 Milliards euros. $n-\bar{n}$ 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.

Advantages of our 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 $\sim 10^4$ over the existing PF1/ILL result in terms of the oscillation probability could be achieved

Estimation of the oscillation probability

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

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

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

An example of copper neutron guide

We will use copper as the material of the neutron guide walls due to appropriate values of the optical potential and good accuracy of its theoretical calculations: $U_{\bar{n},Cu} = (220 + i10)\, neV$. Note, however, that even a better material can be (probably) found in the future.

Characteristic phase-shift times

Then, $\tau_{hor}^{\Delta\varphi,\bar{n}} = \frac{D}{\overline{|v_{hor}|}} \cdot \frac{\sqrt{V_n V_{\bar{n}}}}{2\sqrt{\overline{e_{hor}}}\left(\sqrt{V_n} - \sqrt{V_{\bar{n}}}\right)} \sim 45\ s$ and

$$\tau_{vert}^{\Delta\varphi,\bar{n}} = \frac{\overline{|v_{vert}|}}{g} \frac{\sqrt{V_n V_{\bar{n}}}}{\sqrt{\overline{e_{vert}}}\left(\sqrt{V_n} - \sqrt{V_{\bar{n}}}\right)} \sim 4.5\ s$$

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.

Characteristic annihilation times

$$\tau_{hor}^{\rho,\bar{n}} = \frac{D}{\overline{|v_{hor}|}} \frac{(V_n)^{3/2}}{W_{\bar{n}}\sqrt{\overline{e_{hor}}}} \sim 60\ s,$$

$$\tau_{vert}^{\rho,\bar{n}} = \frac{2\overline{|v_{vert}|}}{g} \frac{(V_n)^{3/2}}{W_{\bar{n}}\sqrt{\overline{e_{vert}}}} \sim 6\ s.$$

$\tau_{vert}^{\rho,\bar{n}}$ 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 ~10^3[m/s]*6sec*2 ~12km (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

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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.

References

References on F-ND reflectors for VCN:

- V.V. N., U. Koester, M. Dubois, N. Batisse, L. Frezet, A. Bosak, L. Gines, O. Williams (2018). *Fluorinated nanodiamonds as unique neutron reflector*, CARBON 130:799;

- V.V. N., M. Dubois, Ph. Gutfreund, E.V. Lychagin, A.Yu. Nezvanov, K.N. Zhernenkov (2018). *Effect of nanodiamond fluorination on the efficiency of quasi-specular reflection of cold neutrons*, PHYS. REV. A 97: 023629;

- V.V. N., V. Gudkov, K.V. Protasov, M.W. Snow, A.Yu. Voronin (unpublished). *A new concept for experiments searching for neutron-antineutron oscillation*.

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Conclusion

- Under certain conditions, anti-neutrons can bounce from (anti)neutron guide walls, without annihilation and lose of coherence with neutrons,
- Theoretical calculations of this reflection are sufficiently precise for planning experiments on neutron-antineutron oscillations as well as for the reliable interpretation of experimental results,
- In horizontal geometry, a gain-factor of $\sim 10^4$ over the PF1 result can be achieved with neutron intensities of PF1B(ILL), projected(PIK), projected(ESS),
- In vertical geometry at a dedicated VCN source a gain-factor of $\sim 3*10^3$ over the PF1 result can be achieved.