Why very cold neutrons could be useful for neutron antineutron oscillations searches

- Neutron-antineutron oscillations,
- Antineutron guides,
- First analysis,
- Advantages of VCNs,
- A possible implementation at ESS.

Neutron-antineutron oscillations

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

A. Addazi et al, *New high-sensitive searches for neutrons converting into antineutrons and/or sterile neutrons at the HIBEAM/NNBAR experiment at the European Spallation Source*, J. Phys. G 48 (2021) 070501

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.

Antineutron guides

V.V. Nesvizhevsky et al, *Experimental approach to search for free neutron-antineutron oscillations based on coherent neutron and antineutron mirror reflection*, Phys. Rev. Lett. 122 (2019) 221802; *Comment on B.O. Kerbikov "The effect of collisions with the wall on neutron-antineutron transitions"* Phys. Lett. B 795 (2020) 135357; K.V. Protasov et al, *Theoretical analysis of antineutron nucleus data needed for antineutron mirrors in neutron-antineutron oscillation experiments*, Phys. Rev. D 102 (2020) 075025

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

A characteristic lifetime of antineutrons in the guide is **1-3 s**

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

Antineutron guides

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**.

A direct 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 difference is on the next page).

Antineutron guides

We ("clock non-reset"):

- 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.

Antineutron guides

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

- **Smaller transversal sizes**,
- **Lower costs**,
- **Larger statistics** (higher accuracy).

For **a larger length**,

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

First analysis

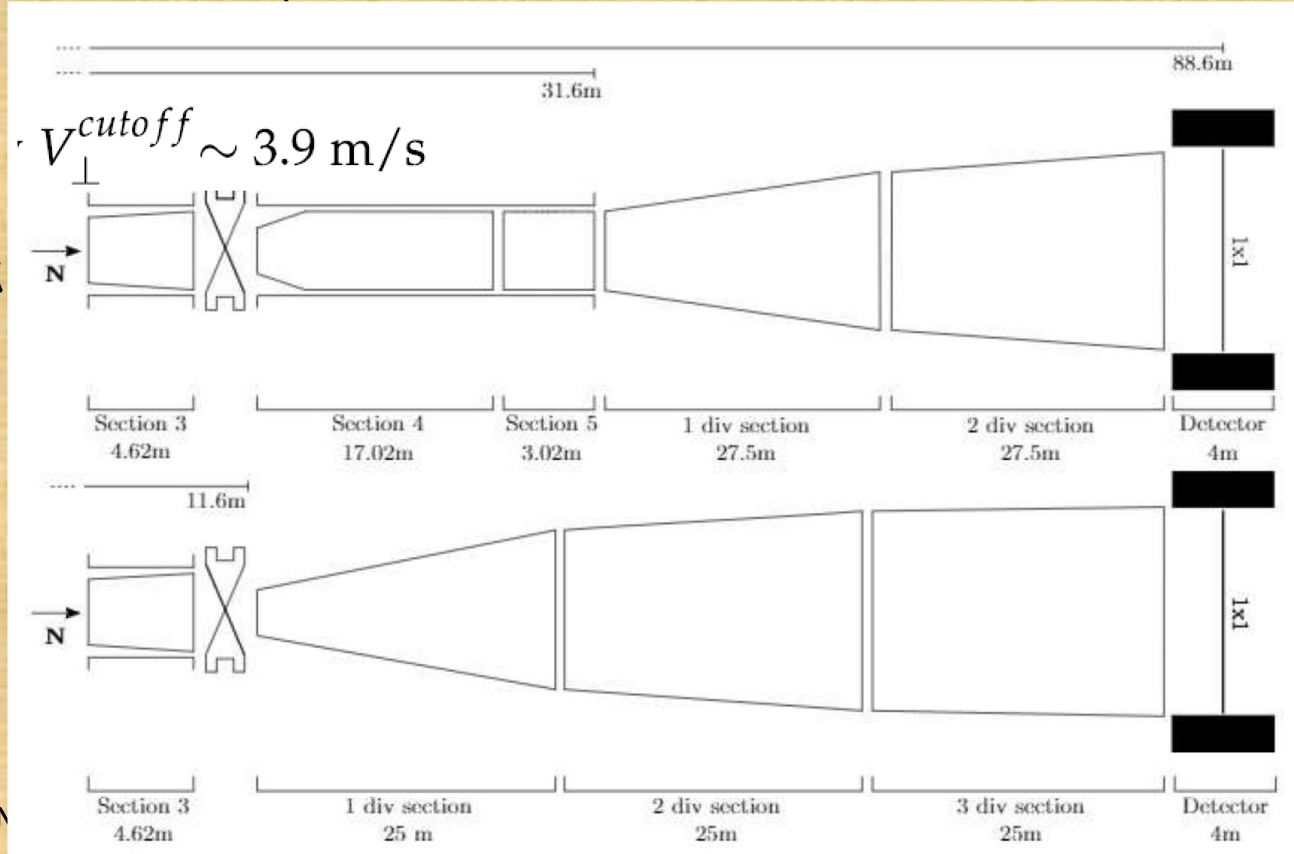
V. Gudkov et al, *A possible neutron-antineutron oscillation experiment at PF1B at the Institut Laue Langevin*, Symmetry 13 (2021) 2314

$$V_F(\bar{n}\mathrm{Cu}) \equiv V_0 - iW = 94 - i27\ \mathrm{neV},$$

A Cooper guide. Both the real and imaginary parts of the scattering length are decreased/increased by 5 standards deviations

The **overall gain** factor over the best existing limit is **3-10 times** (as a function of the chosen configuration)

- Background: **below 1 event**
- Systematics: **virtually absent**



First analysis

ESS would provide a **much higher sensitivity**

An experiment design and sensitivity are going to be analyzed soon

Gain factor (compared to PF1B) include:

- A significantly larger length (quadratic increase in sensitivity),
- A significantly larger solid angle of extracted neutrons (also quadratic increase in sensitivity)

These factors would give an **additional factor of >100**
Lower costs due to the smaller guide and detector sizes, smaller backgrounds from the spallation source, compared to the design without the antineutron guide

First analysis

An uncertainty in the experiment sensitivity estimation is associated with the **uncertainty in the scattering length** of slow antineutrons on the guide wall material.

-for **PF1B**, the time of flight is 0.05 s, much shorter than antineutron storage times, thus it is **negligible**,

-for **ESS**, the time of flight is 0.4 s, $\Delta \mathrm{Im} b_{\bar{n}A} / \mathrm{Im} b_{\bar{n}A} = \Delta \mathrm{Im} a_{\bar{n}A} / \mathrm{Im} a_{\bar{n}A} \sim 0.1$

$\tau_{\bar{n}} / \tau_{\mathrm{obs}} \sim 5.$, and the systematic uncertainty in the estimation of the oscillation time is as small as **0.5%**.

Advantages of VCNs

As the observation time at ESS would be still significantly smaller than the lifetime of antineutrons in the guide, one could try to use **the advantages of the method to its maximum** and decrease the mean neutron velocity.

- Sensitivity increases as the **square** of observation time,
- Neutron flux decreases as the **square** of neutron velocity,
- Thus **sensitivity is the same for the same phase-space density**.

However, a **dedicated VCN source** would significantly increase the phase-space density!

A possible implementation at ESS

The design kindly provided by Luca Zanini

The proposal:

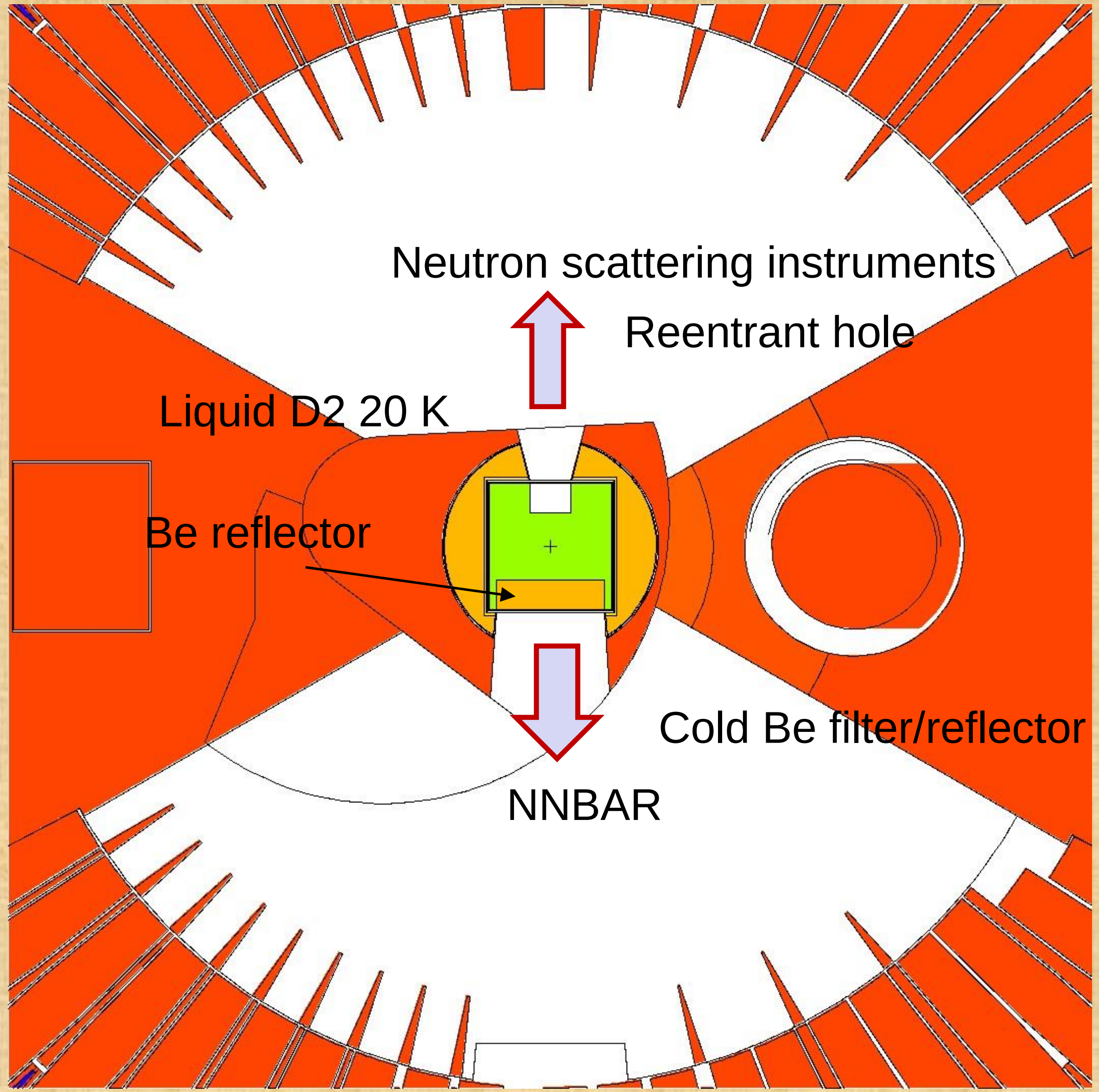
to replace

Be reflector by

solid-deuterium

VCN converter,

Or to put on top of the reflector



A possible implementation at ESS

- An **optimum position** (close to the maximum flux of cold neutrons),
- An **optimum incident neutron velocity** (for the production of VCNs),
- A very **large cross-section** – thus a very large **total VCN flux**, delivers VCNs to **many beam positions**,
- The thickness (**say, 5 cm**) is a compromise between the heat load to solid deuterium and the VCN extraction depth,
- No problems with neutron scattering on the **density inhomogeneity** (an important problem for UCNs but virtually absent for VCNs),
- Profits from the **pulsed structure** of the ESS neutron source,
- Could be used to **produce UCNs** (see another talk tomorrow)