«Enhanced Directional Extraction of Very Cold Neutrons Using a Diamond Nanoparticle Powder Reflector»

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Very Cold Neutrons

Very cold neutrons (VCN):

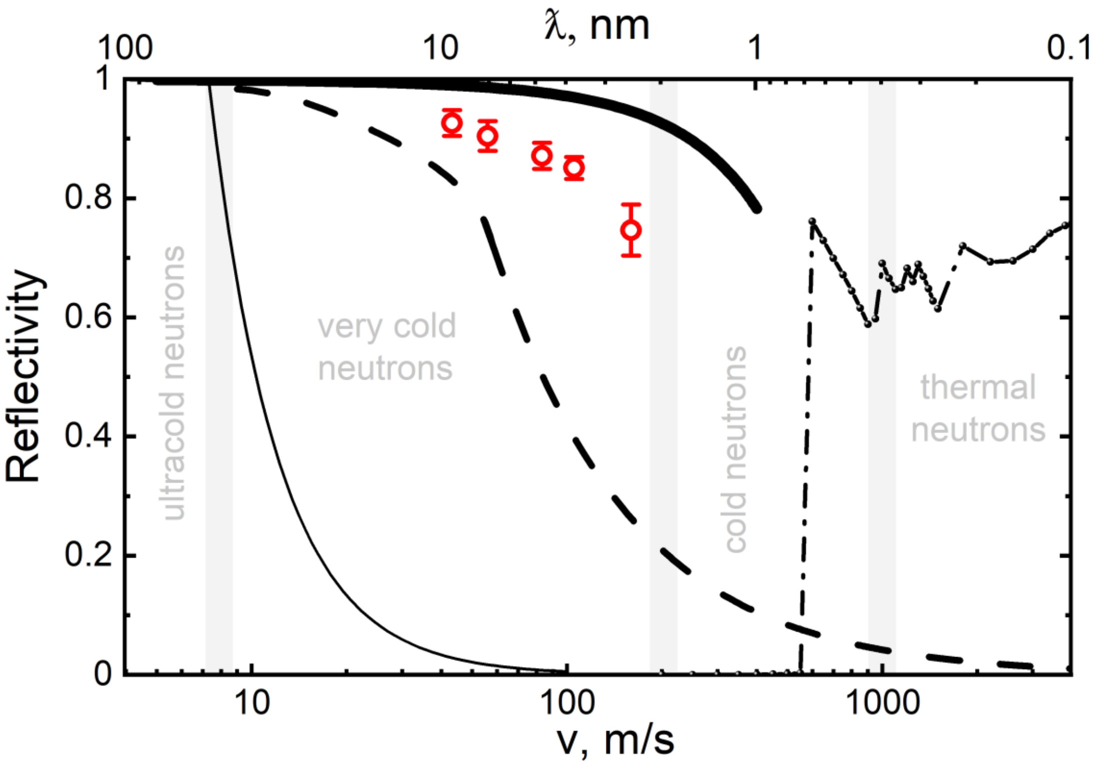
- the typical wavelengths are 2.5–60 nm
- the velocities are 20–160 m/s;
- the energies are 0.25–130 μeV;
- the temperatures are 3×10^{-3}–1.55 K.

Articles about the VCN applications and prospects:

R. Golub, *Phys. Lett. A*, 38, 1972. 10.1016/0375-9601(72)90465-3
V.V. Golikov, V.I. Lushchikov, and F.L. Shapiro, *JETP*, 37, 1973. URL
R. Gähler, A. Zeilinger, *Am. J. Phys.*, 59, 1991. 10.1119/1.16540
E.M. Rasel, et al. Springer, 1994. 10.1007/978-1-4615-2550-9_36
G. van der Zouw, et al. *NIM-A*, 440, 2000. 10.1016/S0168-9002(99)01038-4
R. Georgii, et al. *Neutron News*, 18, 2007. 10.1080/10448630701328471
V.V. Nesvizhevsky, *Rev. Mex. de Fis. S*, 57, 2011. URL

Dedicated workshops:

21-24 August 2005, Argonne National Laboratory, USA. URL
13-14 February 2006, Paul Scherrer Institute, Switzerland.
27-28 April 2016, Oak Ridge National Laboratory, USA. URL
2-4 February 2022, European Spallation Source, Sweden. URL
9-10 May 2023, European Spallation Source, Sweden. URL
8-11 April 2024, Institute of Nuclear Physics, Kazakhstan. URL



The reflection probability for isotropic neutrons with different velocities.

$$U_{eff} = \frac{4\pi\hbar^2}{2m} n b_{coh} \qquad U_{eff} \sim 100\ neV$$

VCN Applications

The VCN advantages are:

- long time of observation;
- large angles of reflections from mirrors;
- larger phase shift and as result more sensitive to contrast variation;
- large coherent length;
- large capture cross-section and big contrast at transmission;
- structure analysis of large molecular complexes; etc.

The main disadvantage is a low flux intensity!

Neutron techniques:

- SANS;
- spin-echo;
- TOF spectroscopy, in particular, high-resolution inelastic scattering;
- reflectometry, diffraction, microscopy, holography, tomography, etc.

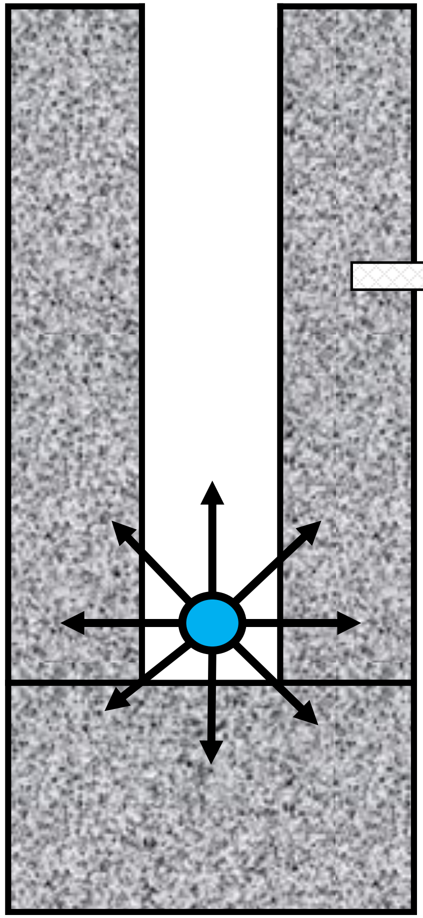
Fundamental Physics:

- a search of extra-short-range interactions at neutron scattering;
- experiments with neutrons in a whispering gallery;
- beam experiment to measure of the neutron decay, etc.

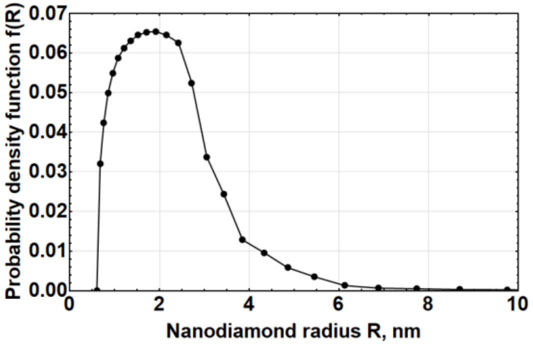
VCN Reflector

Criteria for the VCN reflector are <u>minimum losses</u> and <u>maximum reflection</u>.

Detonation nanodiamonds (DND) are the ideal candidate!



The possible scheme of the VCN source.



$$\boxed{P_{REF}^{max}:\ R_{opt} \approx 0.27\lambda}$$

$R_{opt}(\lambda) \approx 0.7 - 4.3\ nm,$
$\lambda \in [26, 160]$ Å
or $v \in [25, 150]\ m/s$

Positive Factors:

size distribution;
$b_{c.sc.}^{C} = 6.65\ fm;$
$\sigma_{c.sc.}^{C} = 5.55\ b;$
$\sigma_{abs}^{C} = 3.5\ mb;$
$\sigma_{in.sc.}^{C} \to 0\ (T \to 0);$
$\rho^{Diamond} \approx 3.5\ g/cm^3.$

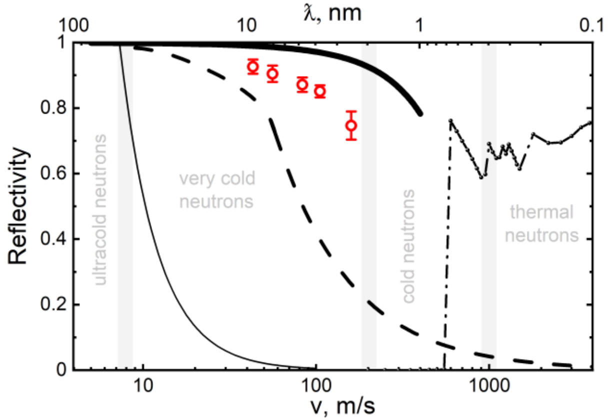
$P_{REF} \sim 95\%$

Negative Factors:

~10 at. % of hydrogen,
$\sigma_{abs}^{H} = 0.33\ b;$
$\sigma_{in.sc.}^{H} = 108 \pm 2\ b;$

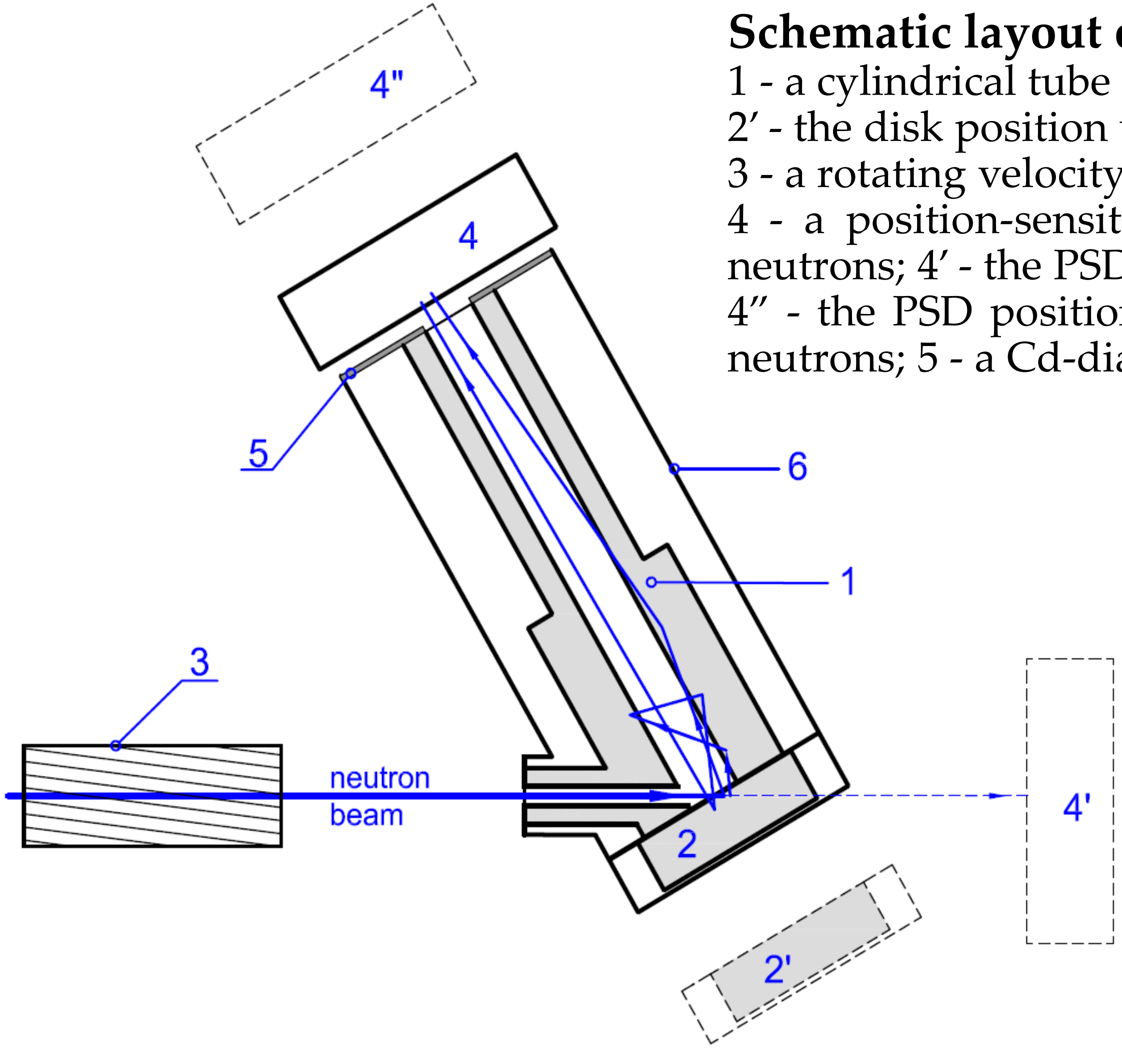
Implemented solutions:

<u>the fluorination of DND</u>
$C/H = 7.4 \pm 0.2$ (before)
$C/H = 430 \pm 30$ (after)



The reflection probability for isotropic neutrons with different velocities.

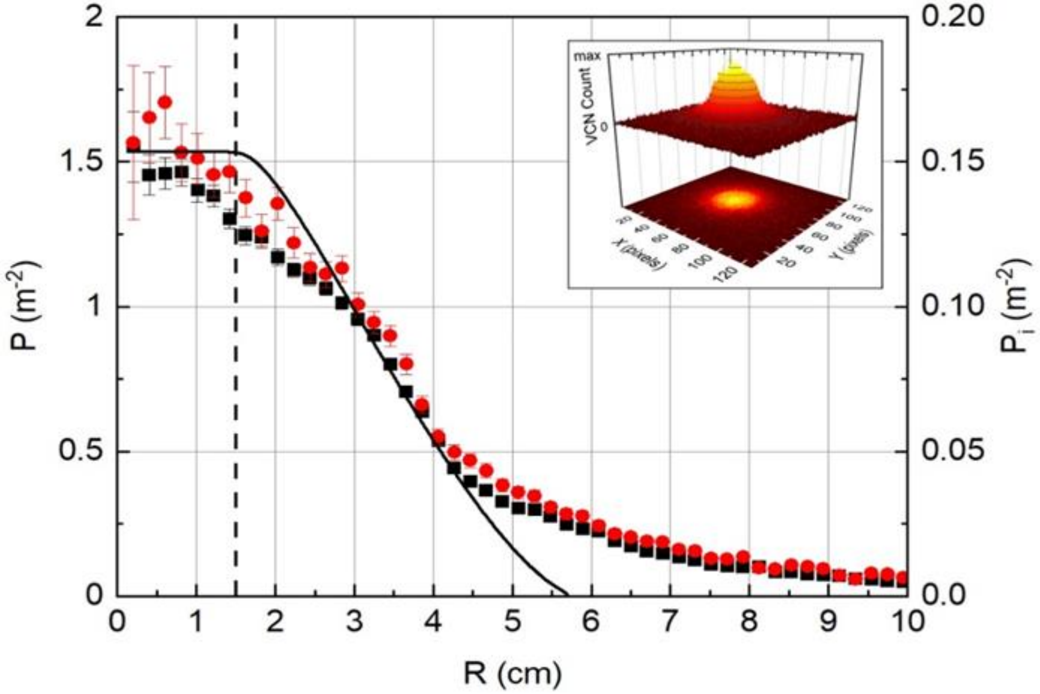
Experimental Extraction System for Very Cold Neutrons



Schematic layout of the experimental setup.
1 - a cylindrical tube made of reflector; 2 - a reflector in the disk shape;
2′ - the disk position when measuring the incident beam flux;
3 - a rotating velocity selector with screw slits;
4 - a position-sensitive detector (PSD) for measuring the flux of escaping neutrons; 4′ - the PSD position when measuring the incident beam flux;
4″ - the PSD position when measuring the angular distribution of escaping neutrons; 5 - a Cd-diaphragm; 6 - an evacuated volume.

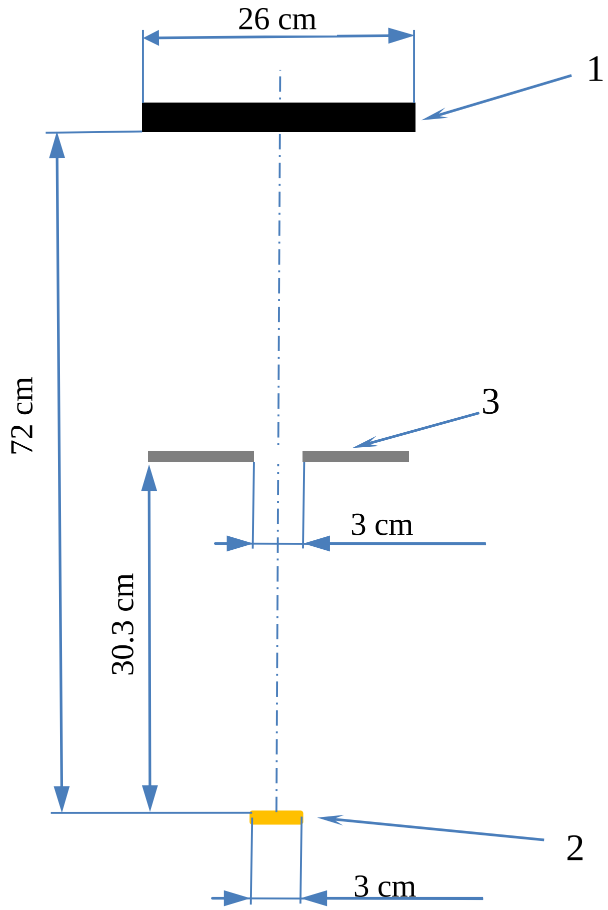
Photos of an evacuated volume of the reflector (on left) and the installation setup (on right).

Experimental Results



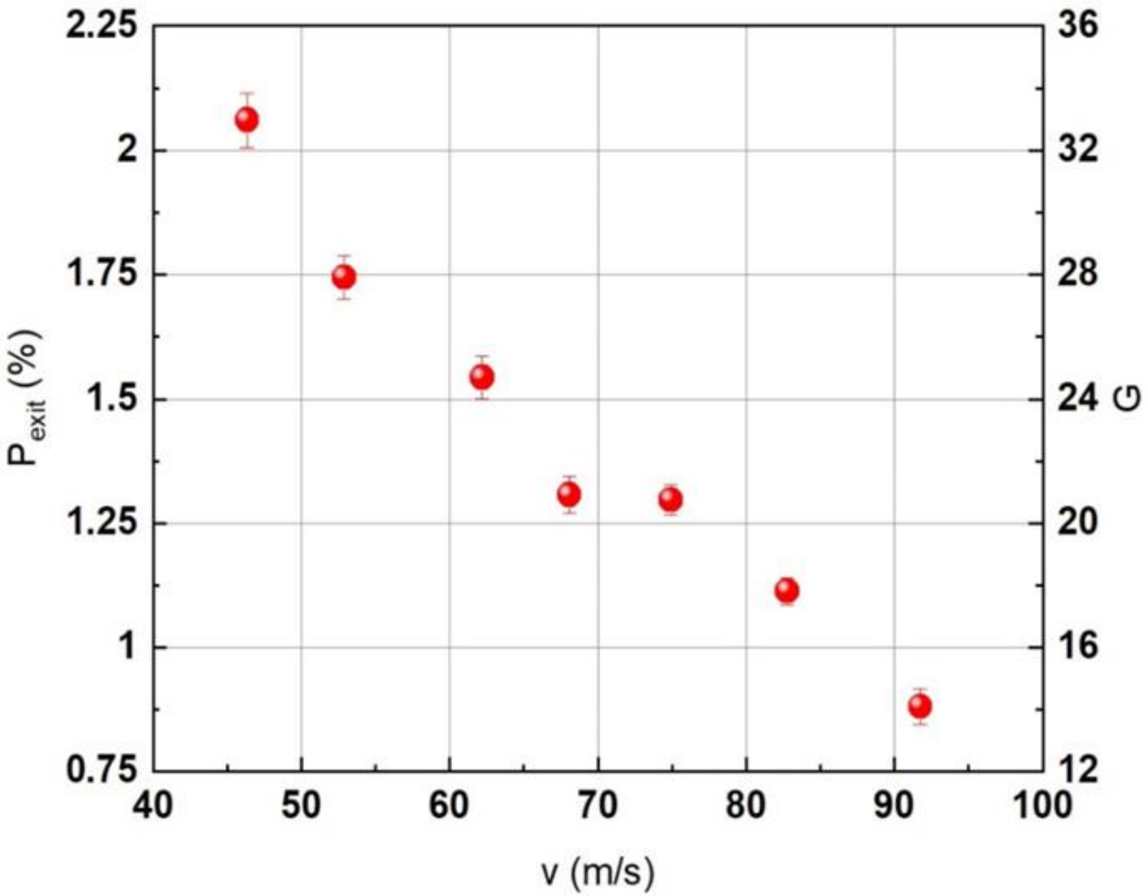
The radial dependence of the specific probability of VCN detection.
Experiments: ● — 57 m/s, ■ — 75 m/s.

Right axis and solid line indicate the specific probability of VCN detection calculated for the homogeneous isotropic source. Vertical dashed line stands for the reflector cavity and the Cd diaphragm radii. The insert shows a map of the PSD counts by pixels for ~75 m/s.

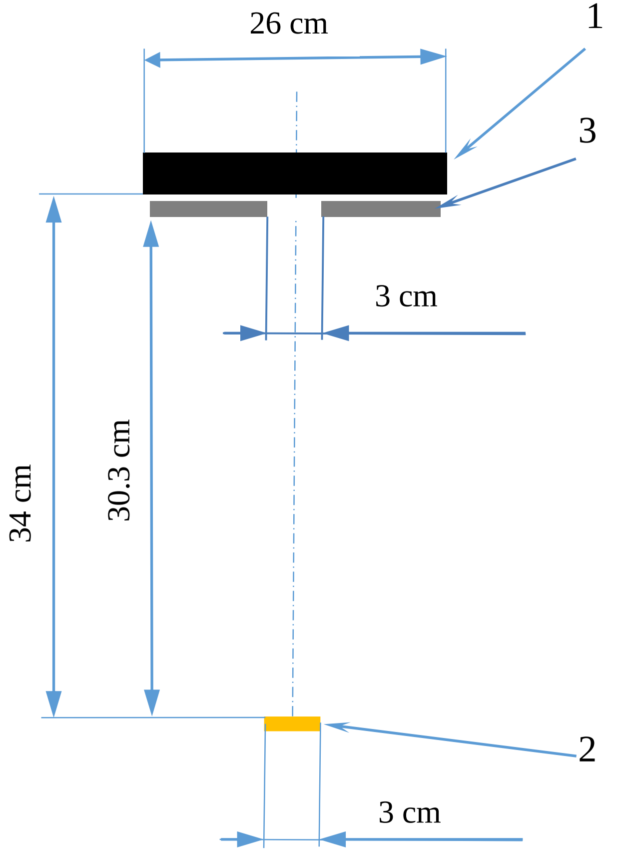


Geometry for calculating an isotropic VCN source:
1 — a position-sensitive detector (PSD) ; 2 — the isotropic source of VCN; 3 — Cd-diaphragm.

Experimental Results

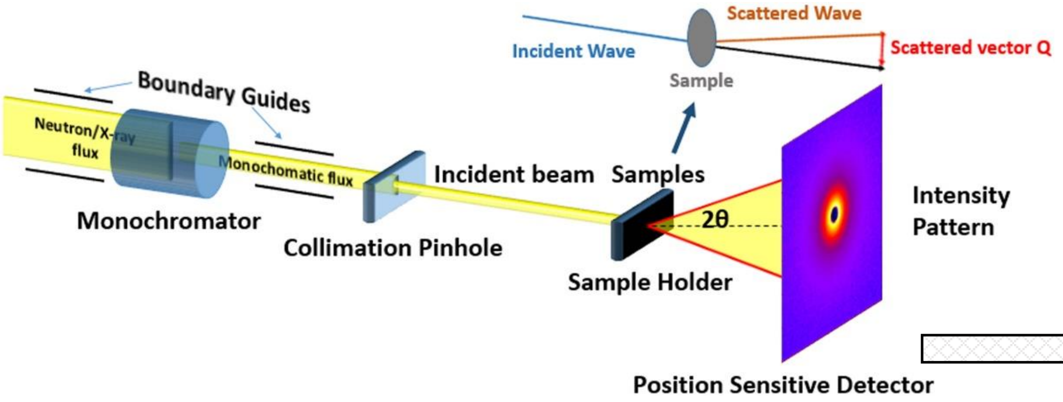


Left axis: the probability of VCN extraction from the reflector.
Right axis: the corresponding gain factor *G*.

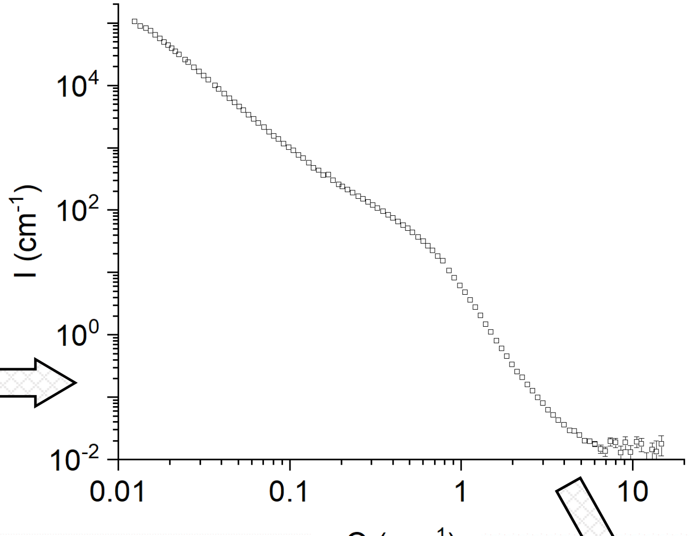


Geometry for calculating an isotropic VCN source:
1 — a position-sensitive detector (PSD) ;
2 — the isotropic source of VCN;
3 — Cd-diaphragm.

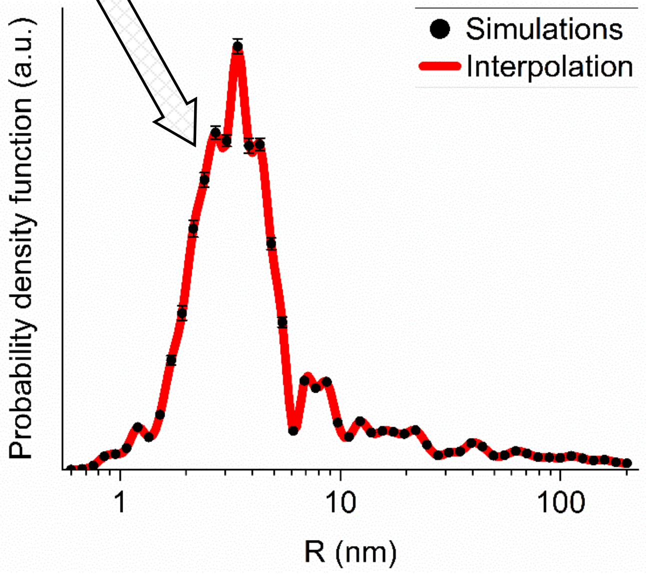
The Model of Neutron Transport in Nanodiamond Powders

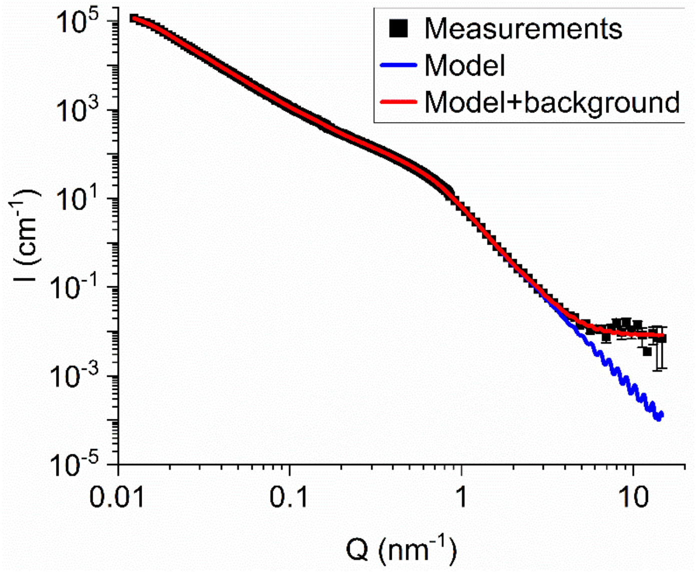


The typical scheme of the SANS experiment.

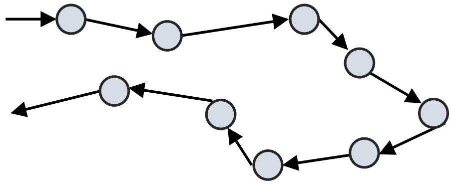


Measured intensity I of scattered neutrons as a function of the transferred momentum Q for the powder of detonation nanodiamonds.

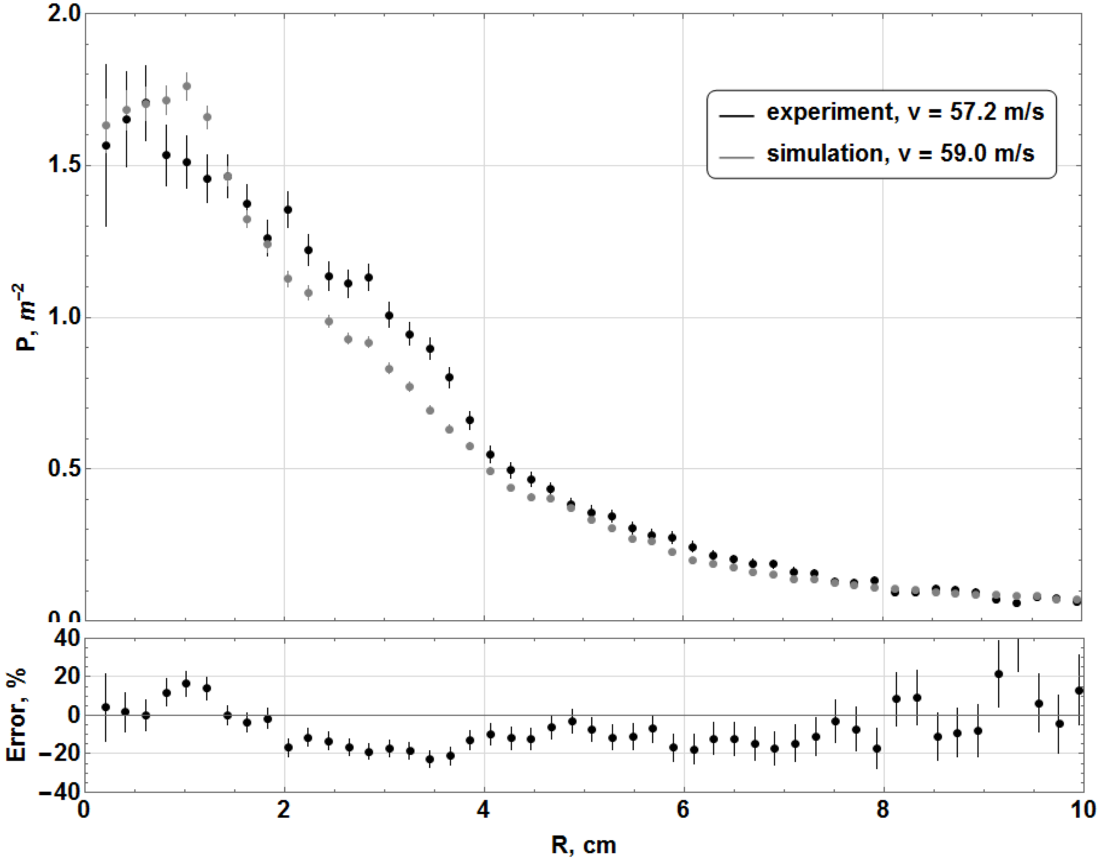




As a result, we get the capability to simulate a multi scattering process via a single scattering cross-section.

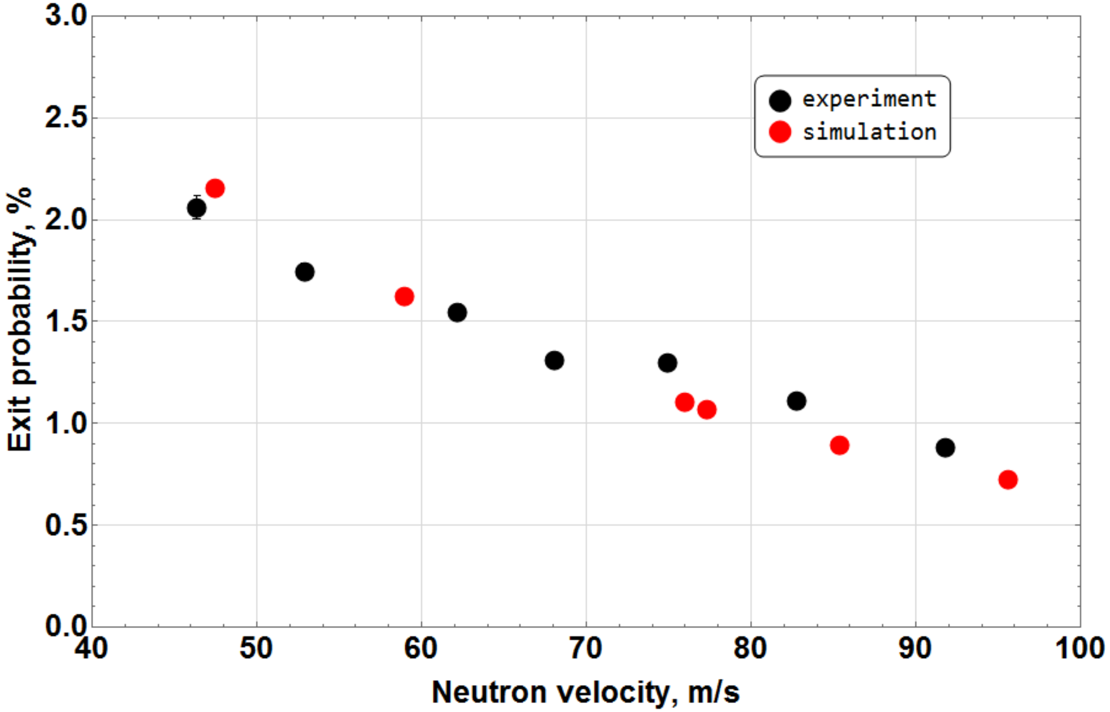


Simulation of the Experiment



The radial dependence of the specific probability of very cold neutron detection.

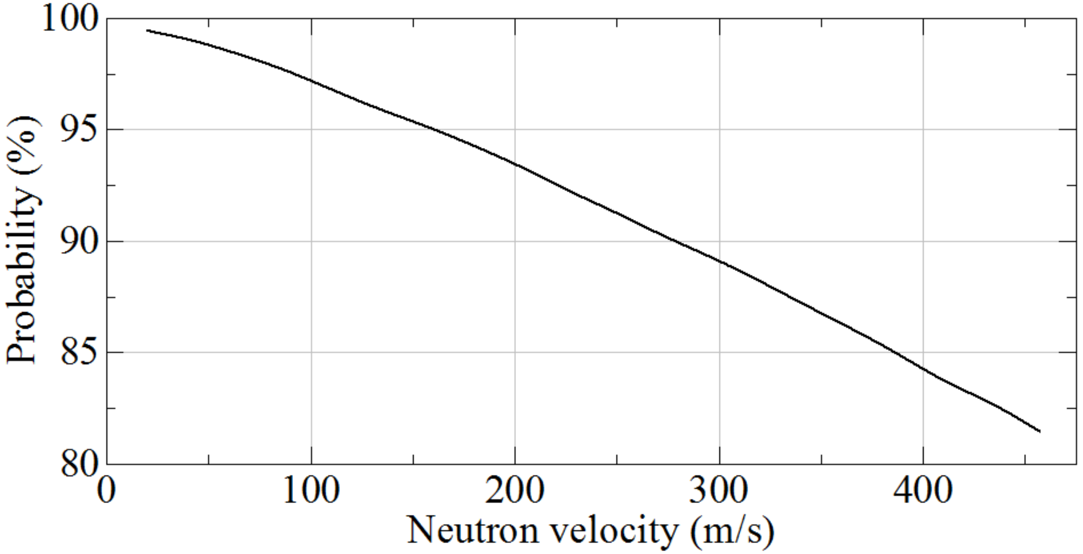
Average error for the point is 11.9 ± 1.4 %.



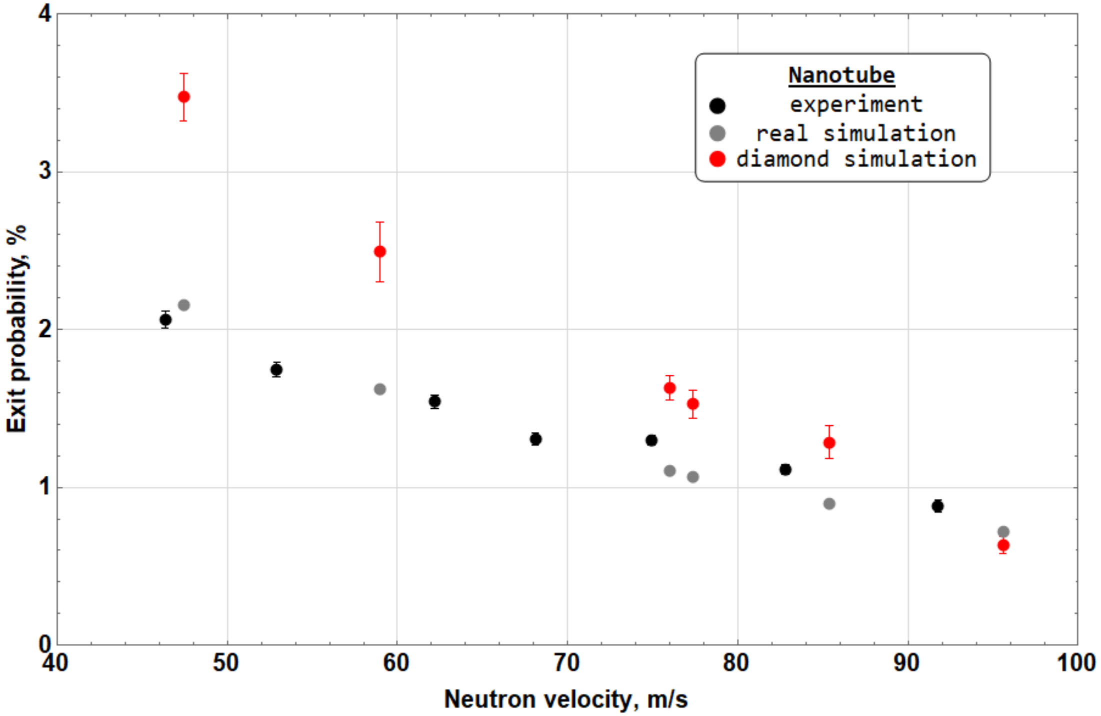
The probability for neutron to escape the reflector through the open end.

The model gives us the opportunity to calculate the reflection coefficient (albedo), as well as the efficiency of the full-scale reflector.

Using the Model for Calculation of Unknown Parameters



Neutron albedo for the semi-infinite flat layer of fluorinated nanodiamonds.



The exit probability for diamond walls instead of the Mg ones.

Potential Applications of Nanodiamond Reflectors

1. Increasing UCN/VCN source intensity at the IBR-2 and/or NEPTUN reactors.
2. Looking for neutron-antineutron oscillations: NNBAR@ESS, the idea of a VCN fountain, etc.
3. VCN storage in material traps to achieve higher densities of low-energy neutrons.
4. Combining both methods for neutron lifetime measurements: to use a VCN beam and measure not the decay products but the change in intensity at the flyby base.

Future Plans

1. Optimization of powder density for neutron reflection.
2. To study of radiation resistance of fluorinated nanodiamonds.
3. Extending the applicability of the transport model to the thermal neutrons by taking into account the crystal structure of nanodiamonds.
4. To study of the time dependence of very cold neutron diffusion in a nanodiamond reflector.
5. To measure the directional extraction of very cold neutrons from a reflector made of purified deagglomerated fluorinated nanodiamond powder.

Conclusions

1. The first experiment demonstrating the possibility of directional extraction of very cold neutrons using a nanodiamond reflector was conducted.
2. The existing model was verified via the simulation of the experiment.
3. Simulation of the experiment expands the possibilities for the analysis and interpretation of experimental data.
4. <u>The obtained results could be used for the development of the ultracold and very cold neutron source in Dubna.</u>

Thank you all for your kind attention!

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