Monte Carlo Simulation of the Extraction System for Very Cold Neutrons Using a Nanodiamond Reflector

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Very Cold Neutrons (VCN)

Ultracold Neutrons Cold Neutrons

- 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 $3{\times}10^{-3}$–1.55 K.

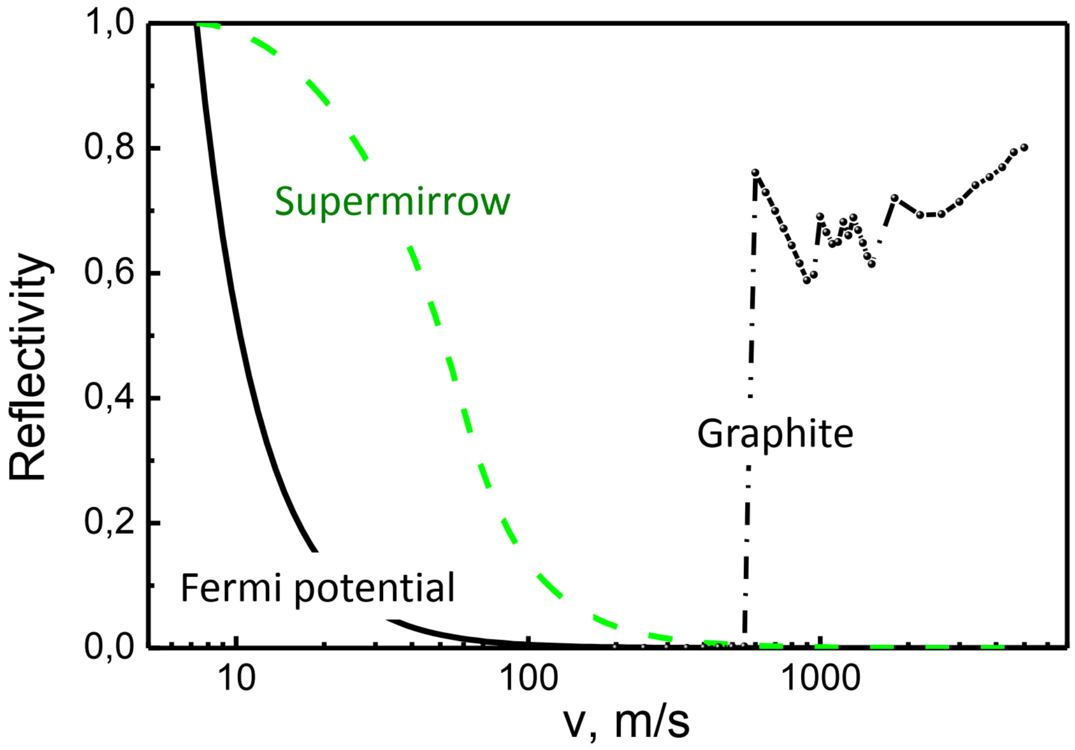


Fig. 1. The reflection probability for isotropic neutrons with different velocities.

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.

<u>The main disadvantage is a low flux intensity!</u>

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

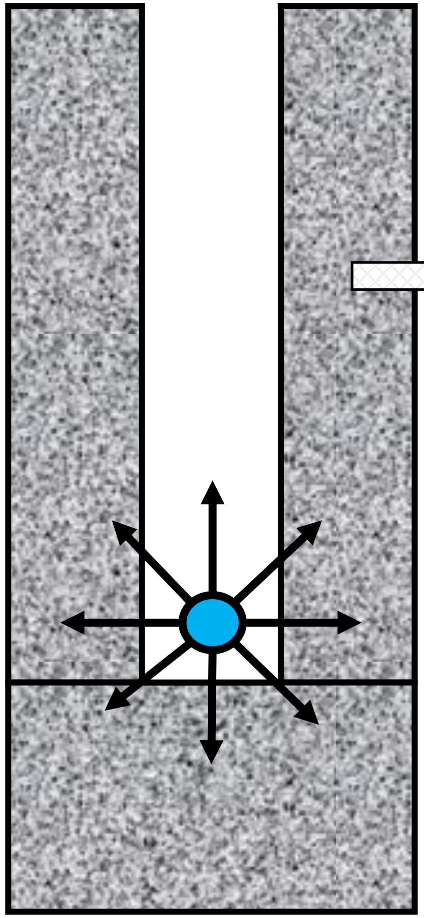
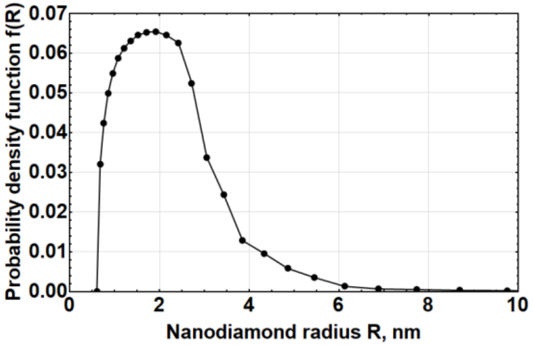


Fig. 2. The possible scheme of the VCN source.

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

Detonation nanodiamonds (DND) are the ideal candidate!



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,
$\sigma_{abs}^{H} = 0.33\ b$;
$\sigma_{in.sc.}^{H} = 108 \pm 2\ b$;
other impurities
< 0.15 at. %

neutron capture — neutron activation

Implemented solutions:

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

<u>the additional purification of DND</u>
$\Sigma_{abs}^{after} / \Sigma_{abs}^{before} \approx 0.58$
$\Sigma_{abs}^{H} \approx 0.2\Sigma_{abs}^{after}$
But still significant activation!

<u>the deagglomeration of DND</u>
$P_{REF}^{after} / P_{REF}^{before} \approx 1.10$
$\rho_{bulk}^{after} / \rho_{bulk}^{before} \approx 3$

Experimental Extraction System for Very Cold Neutrons

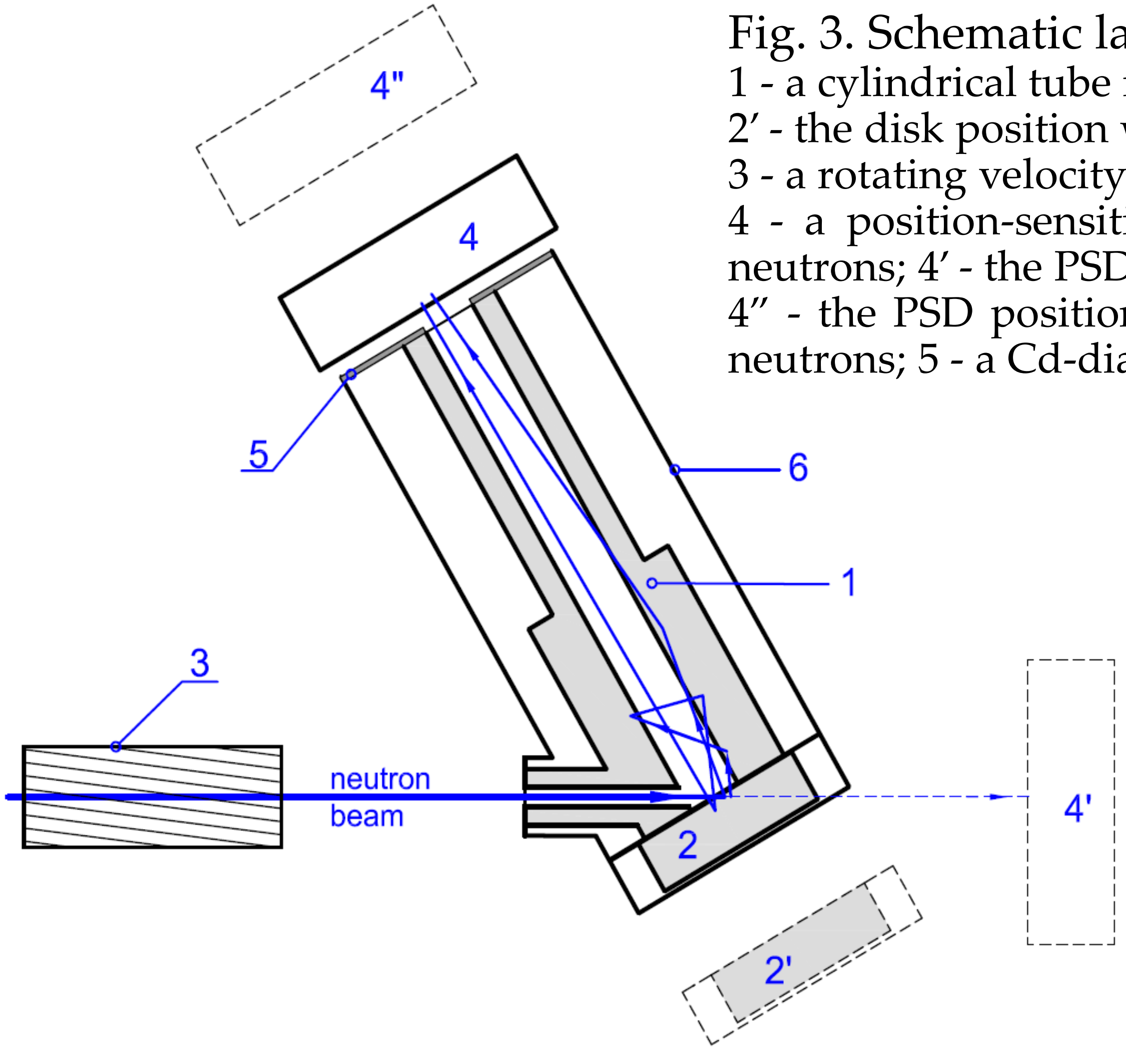


Fig. 3. Schematic layout of the experimental setup.
1 - a cylindrical tube made of reflector; 2 - a reflector in the disk shape;
2′ - the disk position when measuring the incident beam flux;
3 - a rotating velocity selector with screw slits;
4 - a position-sensitive detector (PSD) for measuring the flux 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.

Fig. 4-5. Photos of an evacuated volume of the reflector (on left) and the installation setup (on right).

Experimental Results

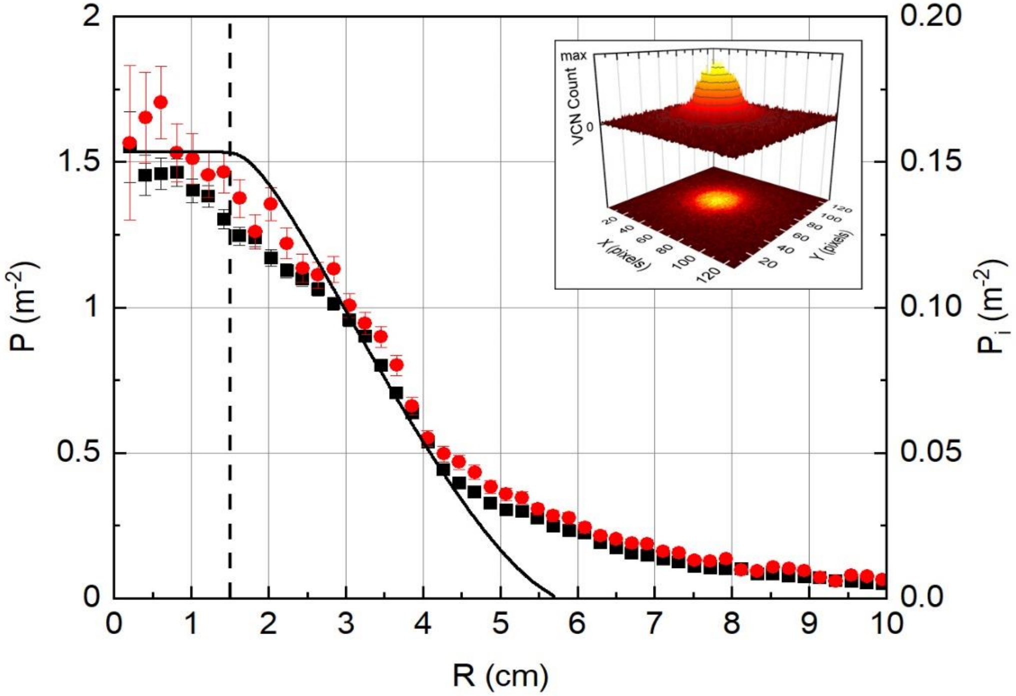


Fig. 6. Left axis and dots correspond to the radial dependence of the specific probability of VCN detection. Round dots correspond to the neutron velocity of ~57 m/s, square dots to ~75 m/s. Right axis and solid line indicate the specific probability of VCN detection calculated for the homogeneous isotropic 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.

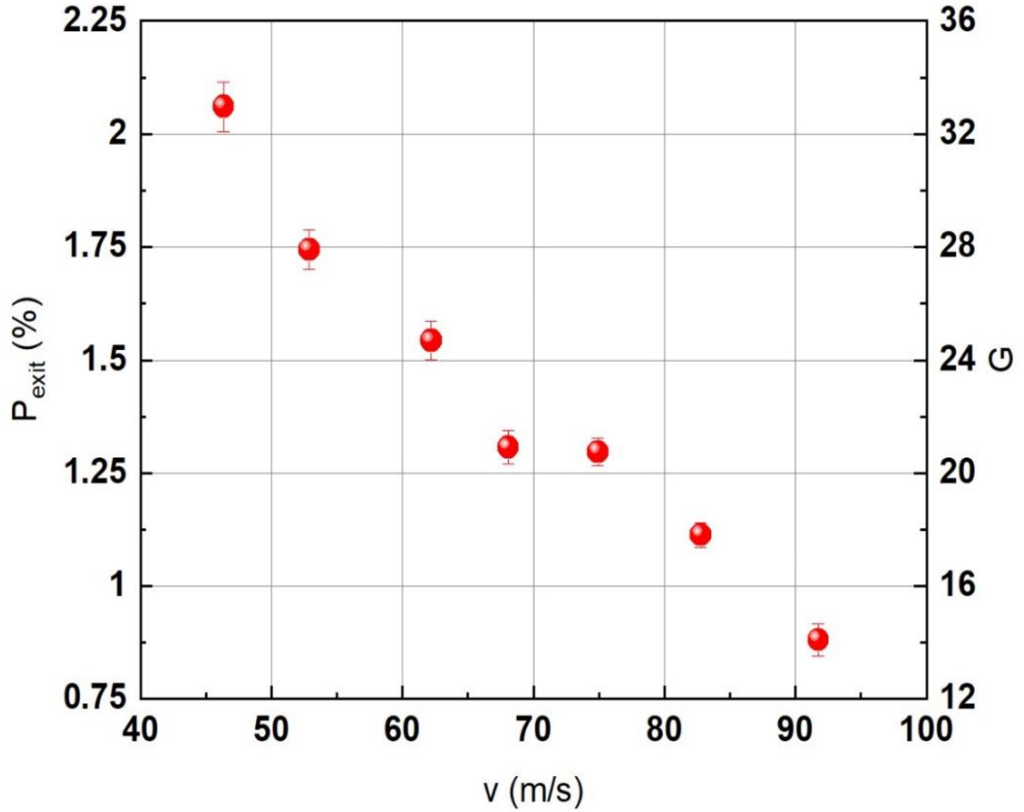


Fig. 7. Left axis: The probability of the VCN escape through the open end of the reflector as a function of VCN velocity. Right axis: gain factor G in the escaping flux relative to the flux that would pass through the diaphragm from a homogeneous isotropic source located at the cavity bottom.

The Model of Neutron Transport in Nanodiamond Powders

Historically it is the model v. 4.0.

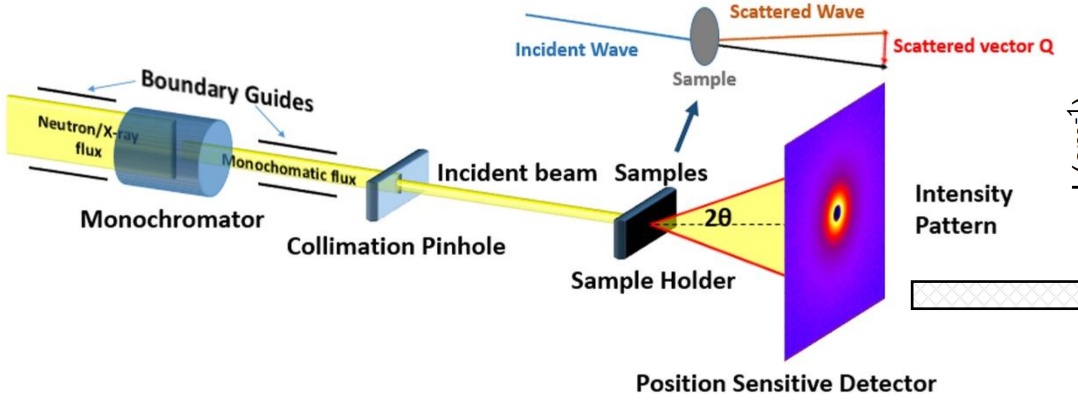


Fig. 8. The typical scheme of the SANS experiment.

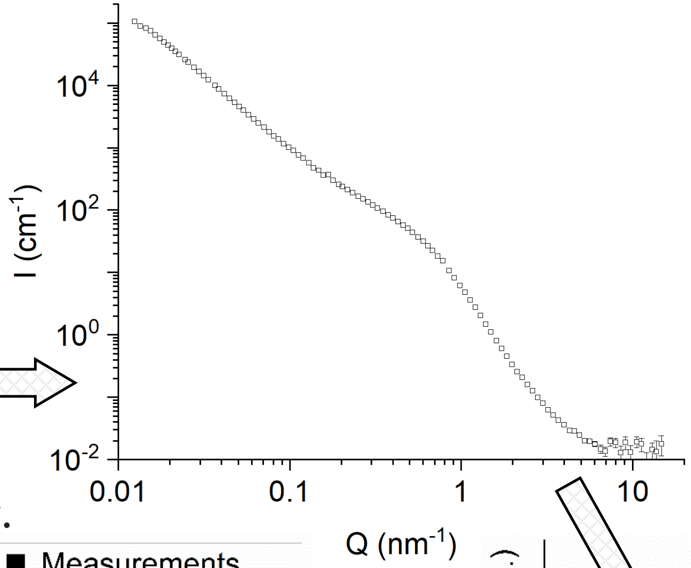
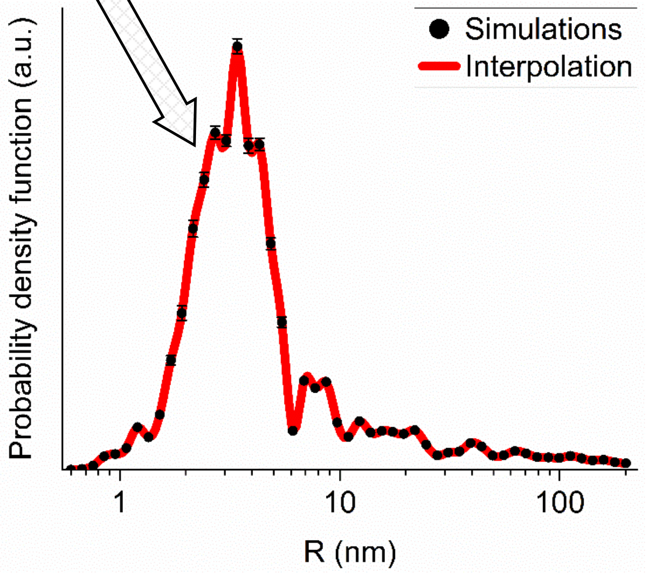
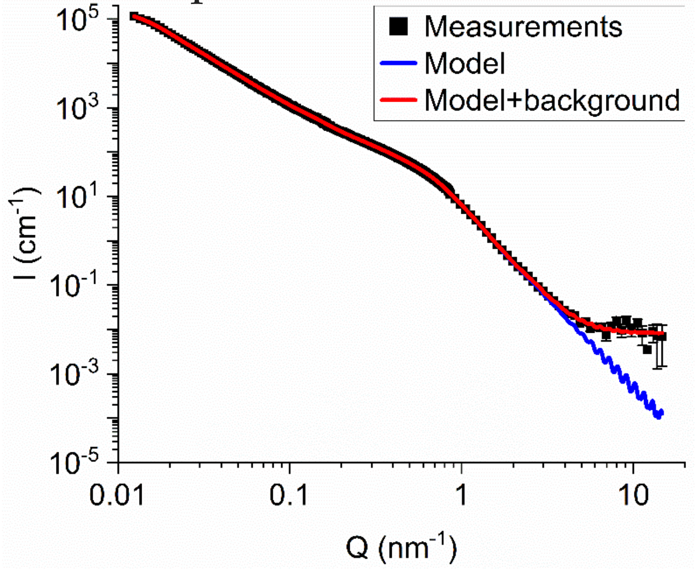
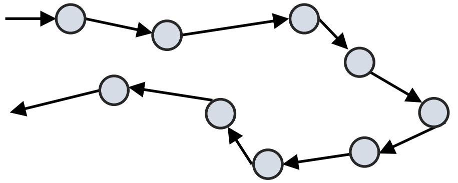


Fig. 9. Measured intensity I of scattered neutrons as a function of the transferred momentum Q for the powder of detonation nanodiamonds.





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



Simulation of the Experiment via Wolfram Mathematica

Materials:
- Fluorinated nanodiamond powder with the bulk density of 0.35 g/cm^3.
- Magnesium foil with thickness of 50 μm.
- Duralumin detector window with a thickness of 4 mm.
- Aluminum flanges at the reflector's exit.
- Air between the reflector's exit and detector.

Processes:
- Elastic neutron scattering.
- Neutron capture by nuclei.
- Consideration of the initial spectra of neutron velocities.

<u>Average simulation performance</u>:

628248 neutron packages per day

Wolfram *Mathematica*

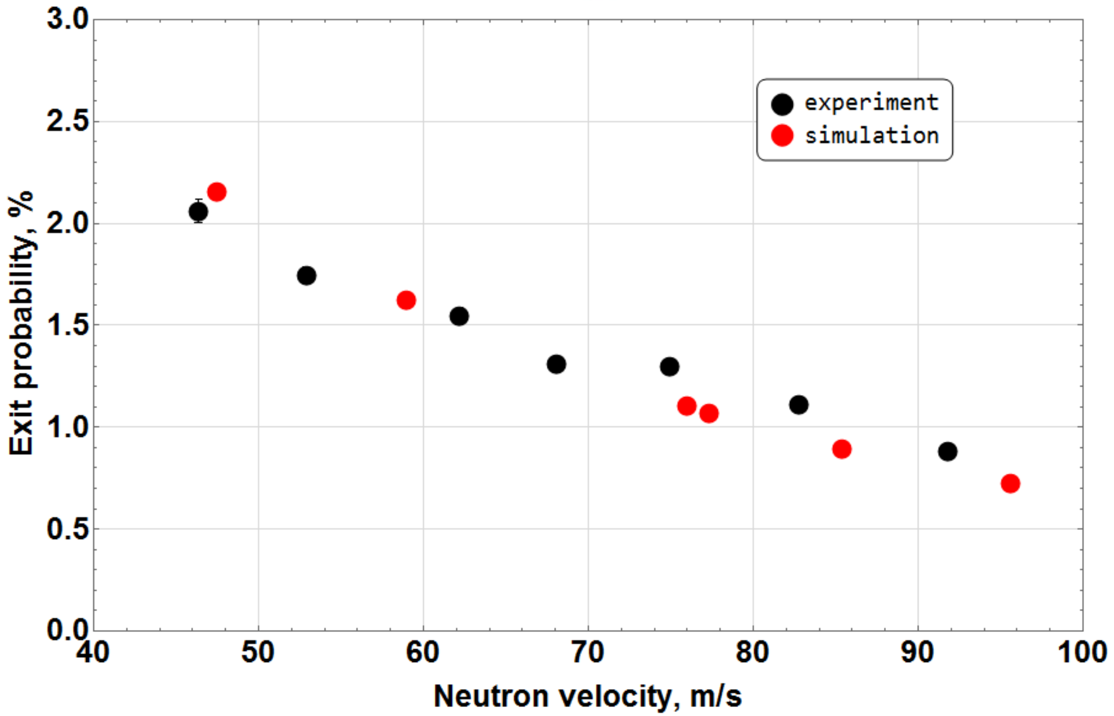


Fig. 10. The probability for neutron to escape the reflector through the open end.

Simulation of the Experiment

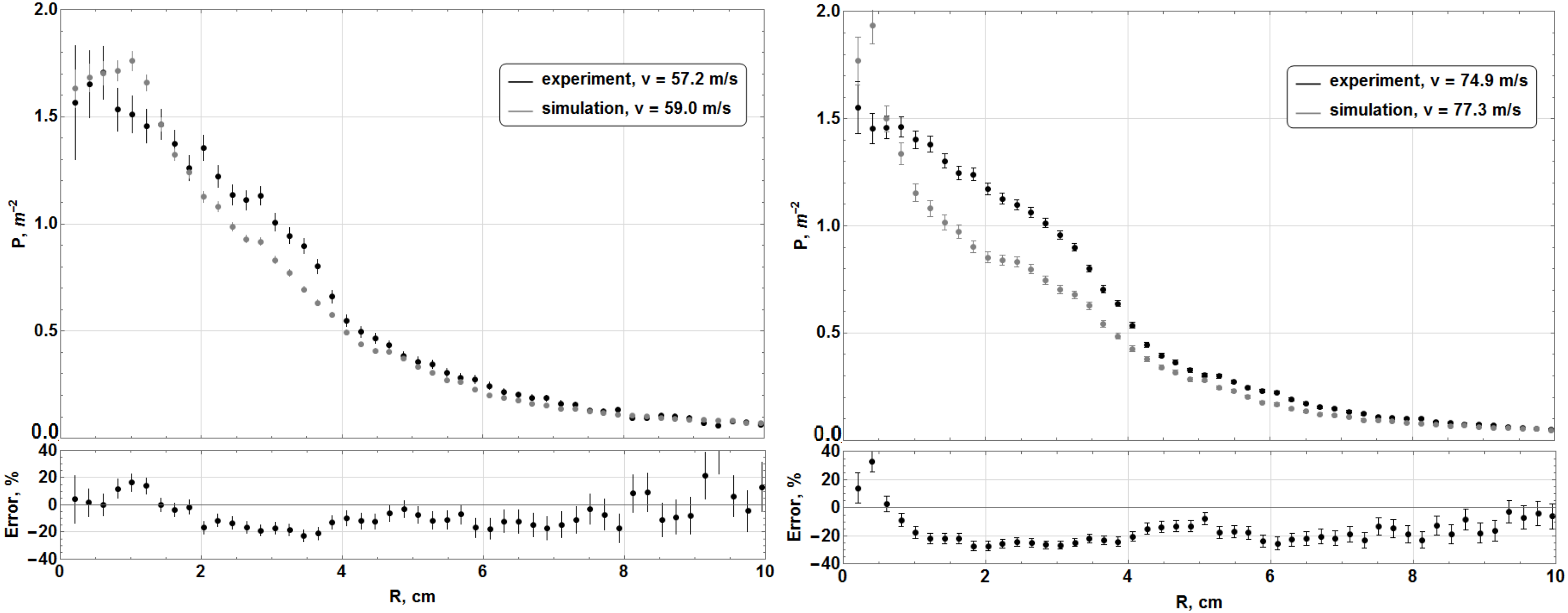
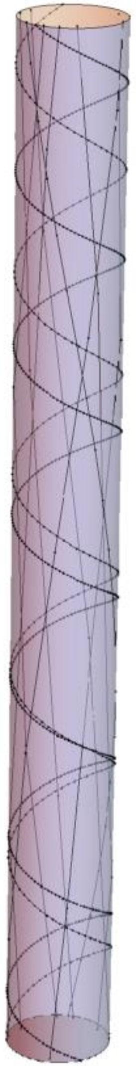


Fig. 11-12. The radial dependence of the specific probability of very cold neutron detection.
Average error for the point is 11.9 ± 1.4 %. Average error for the point is 17.9 ± 0.8 %.

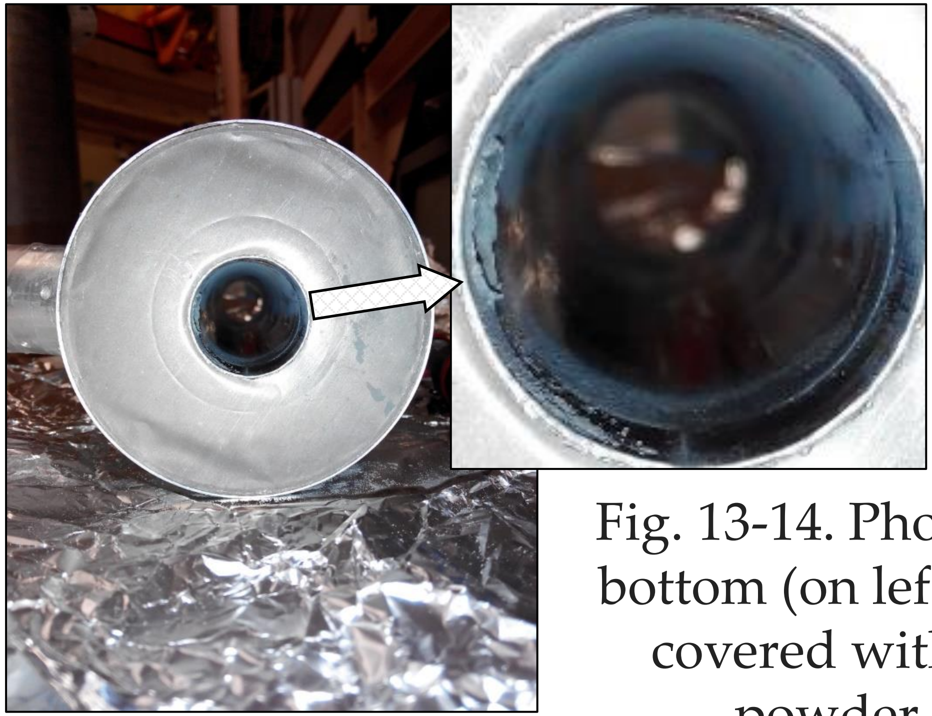
The Discrepancy Between the Simulation and the Experiment



There are neutrons reflecting specularly from the Mg foil walls.

Specular reflection of neutrons is defined by properties of the foil's surface.

The probability of single specular reflection providing the best agreement of simulation results and experimental data is around 61%.



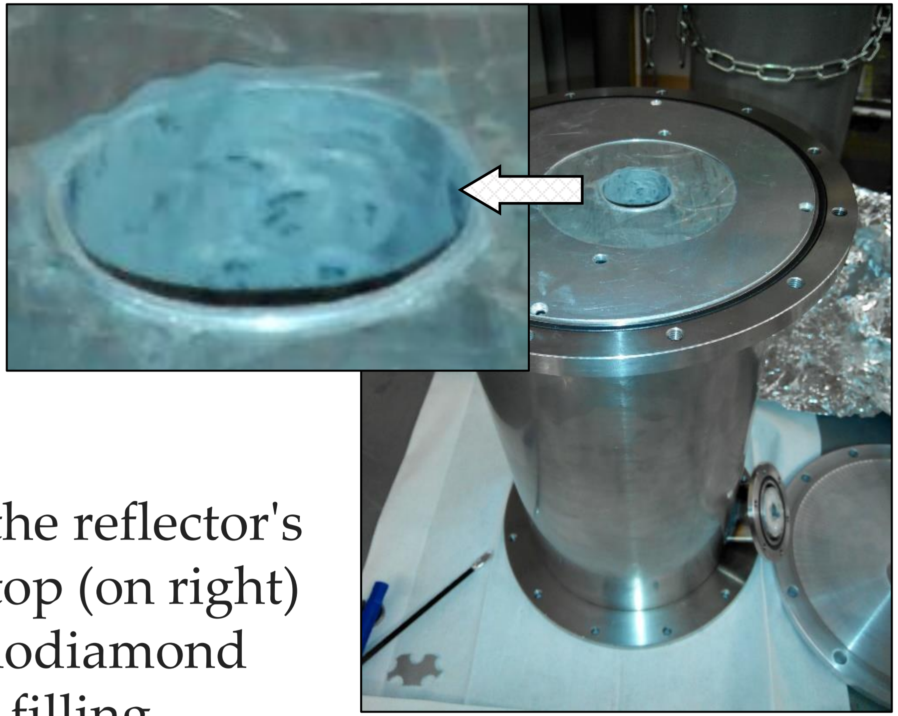


Fig. 13-14. Photos of the reflector's bottom (on left) and top (on right) covered with a nanodiamond powder during filling.

Simulation of the Experiment via Geant4

- The specular reflection of neutrons from the foil walls has not yet been taken into account.
- The direct Monte Carlo method is used instead of the weighted one as in Wolfram Mathematica.

<u>Nevertheless, the average simulation performance</u>:
4526814 neutron packages per day, which is 7.2 times faster than Wolfram Mathematica!

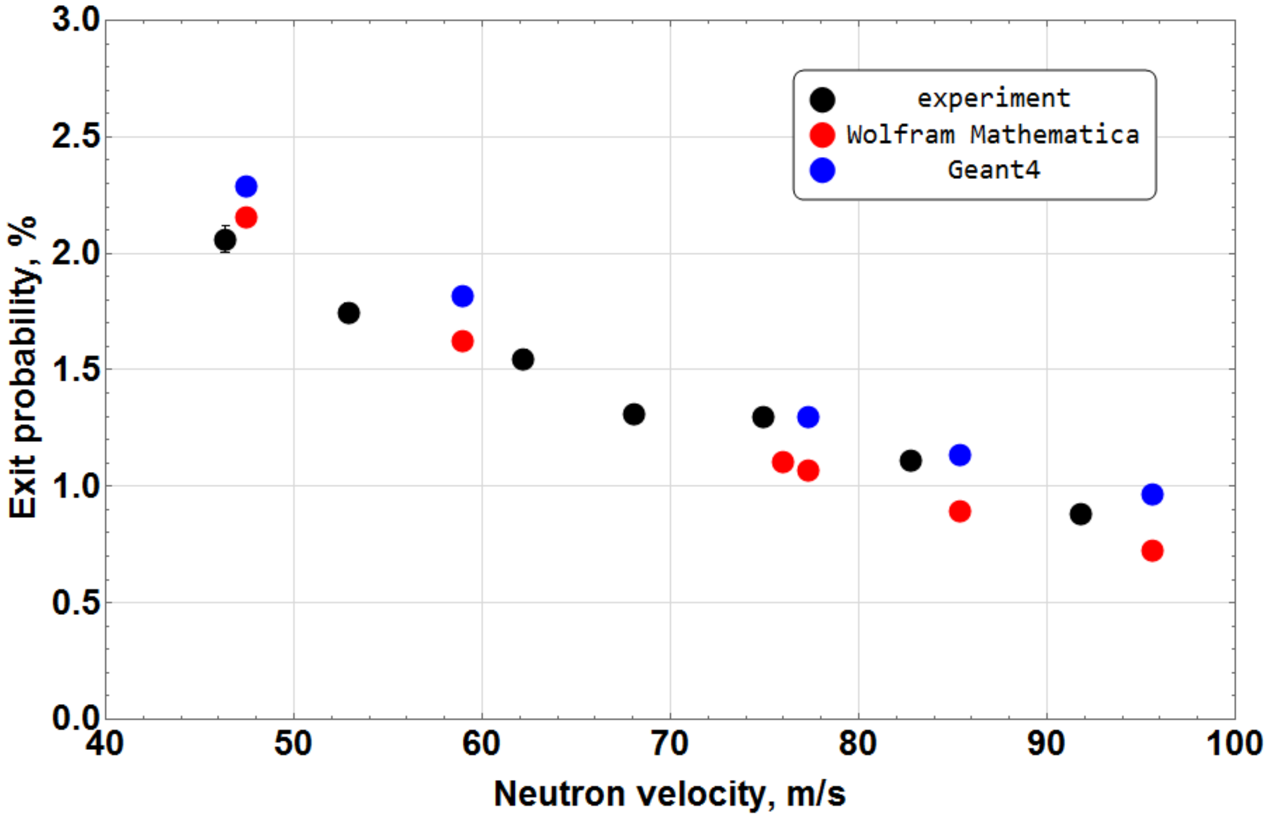


Fig. 15. The probability for neutron to escape the reflector through the open end.

<u>It is expected to be even faster when started on a supercomputer.</u>

Model's Results

- It described an experiment on the directed extraction of very cold neutrons.
- It helped to determine the contribution of specularly reflected very cold neutrons to the total number of extracted neutrons.
- It helped to suggest the reason for the remaining discrepancy between calculations and experiments (the reason is not the model itself but the installation).

What's next?

- Simulating the extraction systems of other geometries.
- Optimization the reflector geometry for a full-size source of very cold neutrons.
- Simulating the focusing systems for low-energy neutrons.

Conclusions

1. The first experiment demonstrating the possibility of directional extraction of very cold neutrons using a nanodiamond reflector was conducted.
2. Verification of the existing model of very cold neutron transport in the nanodiamond powder via the simulation of the experiment on the directional extraction of very cold neutrons.
3. Simulation of the experiment expands the possibilities for the analysis and interpretation of experimental data.
4. A systematic transfer of the very cold neutron transport model from Wolfram Mathematica to Geant4 is underway. The current gain in performance is already more than 7 times.

Thank you all for your kind attention!

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