# MONTE CARLO SIMULATION OF DIRECTIONAL EXTRACTION SYSTEM FOR LOW ENERGY NEUTRONS USING A DIAMOND NANOPARTICLE POWDER REFLECTOR

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## INTRODUCTION

Neutron reflectors are important in neutron physics and the nuclear industry. They reduce neutron losses and redirect fluxes of neutrons with different energies. The active cores of nuclear reactors are usually surrounded by the reflectors of fast or thermal neutrons.

Intense fluxes of very cold neutrons (VCN) with the velocities between 20 and about 200 m/s are of great interest for a variety of applications both in fundamental research and neutron scattering. However, the absence of efficient VCN reflectors was one of the most significant problems for developing the intense VCN sources. The reflectors allow neutrons to be extracted from the source, focused and delivered to experimental facilities.

Until recently, efficient reflectors for neutrons with velocities of 40–500 m/s had not been known. The promising solution to the issue of VCN reflectors is Detonation Nanodiamonds (DND). In a series of previous works it was experimentally shown that DND powders can be used as an effective diffuse reflector of VCN, providing even the possibility to store the VCN in a closed trap. This property of DND was used for experimental studies of the enhanced directional extraction of VCN using a DND reflector [1].

The last results on the simulation of that experiment are presented in this report.

## EXPERIMENT

A scheme of the experimental setup is shown in Fig. 1. The main part of the installation is a fluorinated DND (F-DND) powder reflector. The reflector has the shape of a cylindrical tube (1) (with a variable thickness) closed at one end with a disk (2 and 2′ in Fig. 1). The inner wall of the tube and the top wall of the disk are made of thin (50 μm) pure magnesium foil. The outer wall of the tube is made of aluminum 2 mm thick with holes for pumping out; a layer of filter paper covers the inner surface of the aluminum so that some of the powder does not fly into the pumping system. A layer of F-DND powder was poured between the inner and outer walls.

The geometrical parameters of the reflector are the following:
the internal diameter of the cavity is 30 mm, the length is 300 mm, the diameter of the side entrance hole is 10 mm, the thickness of the powder layer is 30 mm in the disk and in the lower 45 mm part of the cylinder, and it is 10 mm in the rest of the cylinder.
The powder density is 0.35 g/cm$^3$.

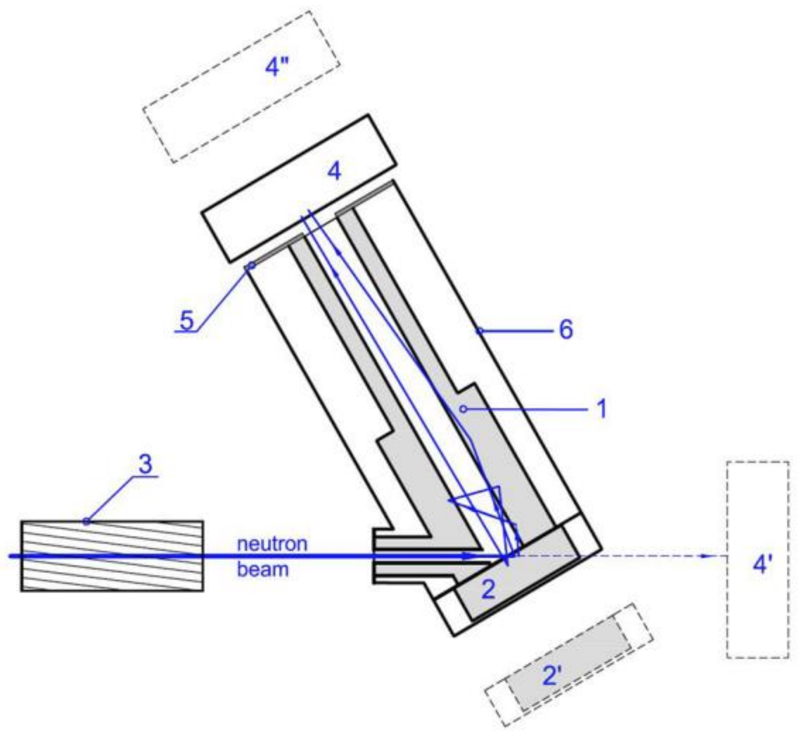


FIG. 1. Schematic layout of the experimental setup: (1)—a cylindrical tube made of reflector; (2)—a reflector in the disk shape; (2′ )—the disk position when measuring the incident beam flux; (3)—a rotating velocity selector with screw slits; (4)—a position-sensitive detector (PSD) for measuring the 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; and (6)—an evacuated volume.

FIG. 2. Photos of an evacuated volume of the reflector (on left) and the installation setup (on right).

## MODELS & SIMULATION

The model of single neutron elastic coherent scattering in the F-DND powder is based on the data of small-angle neutron scattering (SANS). The SANS intensity was described by the calculated intensity for the model-free size distribution of spheres with a diamond bulk density. The obtained size distribution of scatterers was used for calculating the single scattering cross-section for the studied VCN velocities within the first Born approximation

A multiple scattering process was simulated via the obtained single scattering cross-sections and the Monte Carlo method using Geant4 and Wolfram Mathematica.

A VCN beam with a diameter of 0.8 cm felt to the reflector surface on disk 2 (see Fig. 1) and reached out to the PSD by multiple reflections from the walls of the cylindrical tube made of the F-DND.

Materials:
- F-DND with the density of 0.35 g/cm$^3$.
- Magnesium foil with 50 μm thickness.
- 4 mm duralumin detector window.
- Al flanges at the reflector's exit.

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

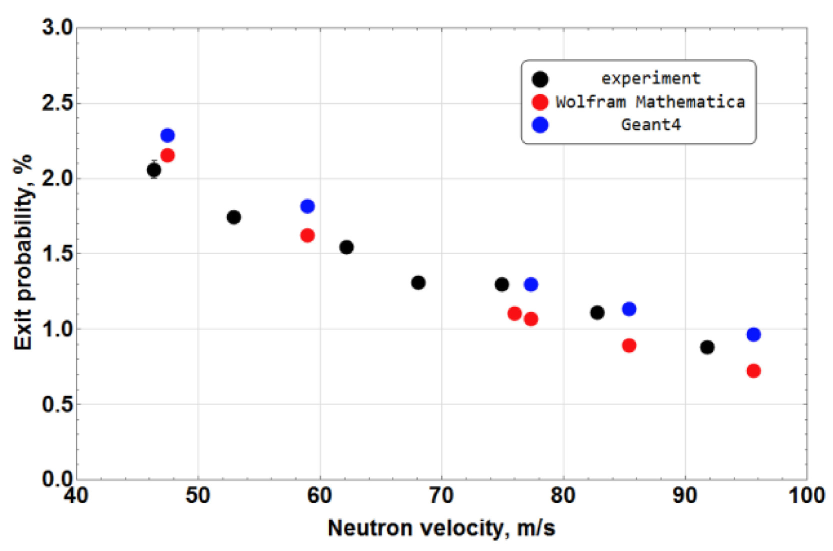


FIG. 3. The total probability of neutron extraction.

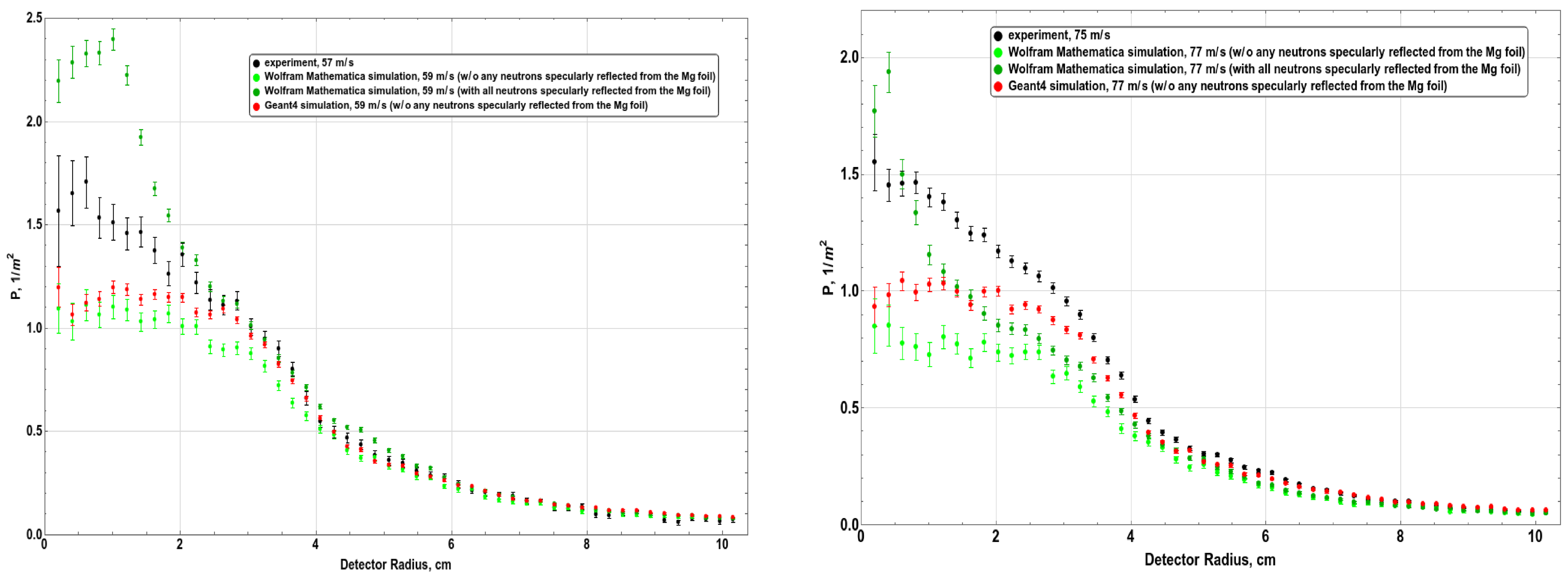


FIG. 4. The radial dependence of the specific probability of very cold neutron detection.

The left axes in Fig. 4 show values of the radial dependence of the specific probabilities of VCN detection, where detector radiuses are a radial distance from the VCN beam axes on the PSD window 4″ (see Fig. 1). Experimental points (black) correspond to detection probabilities measured for two neutron velocity bands with mean values of ∼57 and ∼75 m/s. Geant4 and Wolfram Mathematica simulation results correspond to red and green points, respectively. The specular reflection of VCNs from the Mg foils is not taken into account during simulation on the red and light green points. The dark green points correspond to the neutrons extracted from the reflector due to the specular reflection from the Mg walls without any losses.

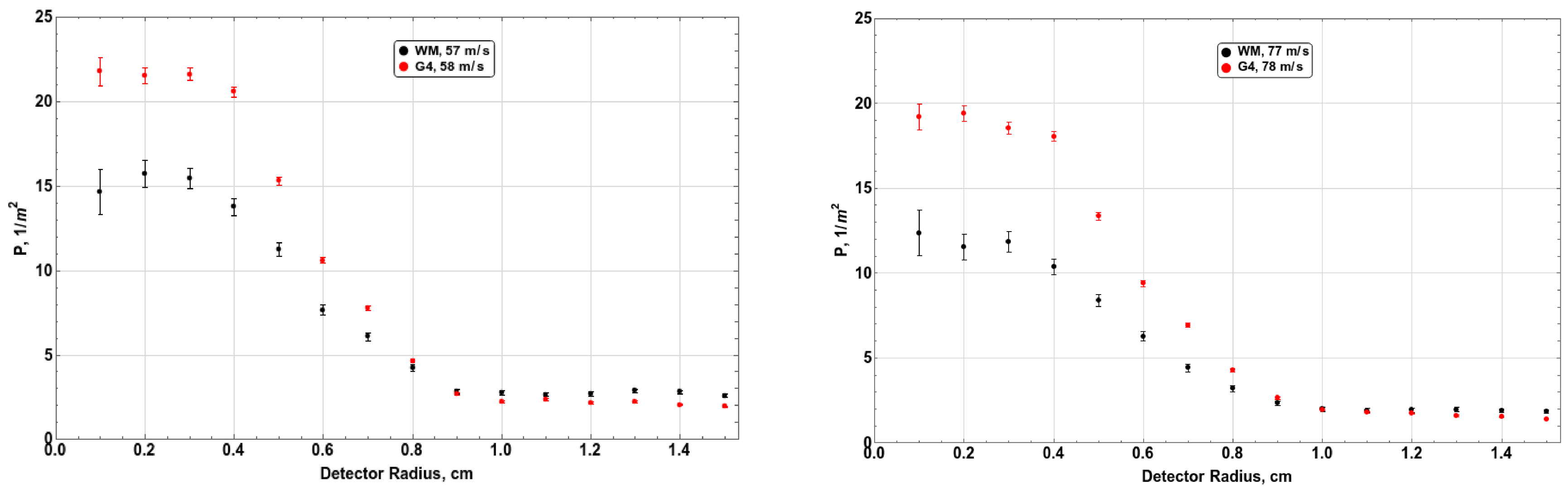


FIG. 5. The probability of very cold neutron detection on the disk reflector.

The graphs in Fig. 5 illustrate the simulation of the probabilities of VCN extraction from the bottom surface 2 (see Fig. 1) to the PSD. VCN spectra have mean velocities of 58 m/s, 78 m/s, and 57 m/s, 77 m/s in Geant4 (red points) and Wolfram Mathematica (black points), respectively. The presented simulation results differ from each other. It might indicate an error in the implemented simulation codes and require a more detailed check.

Fig. 6 shows the distribution of the VCNs extracted from the reflector bottom.

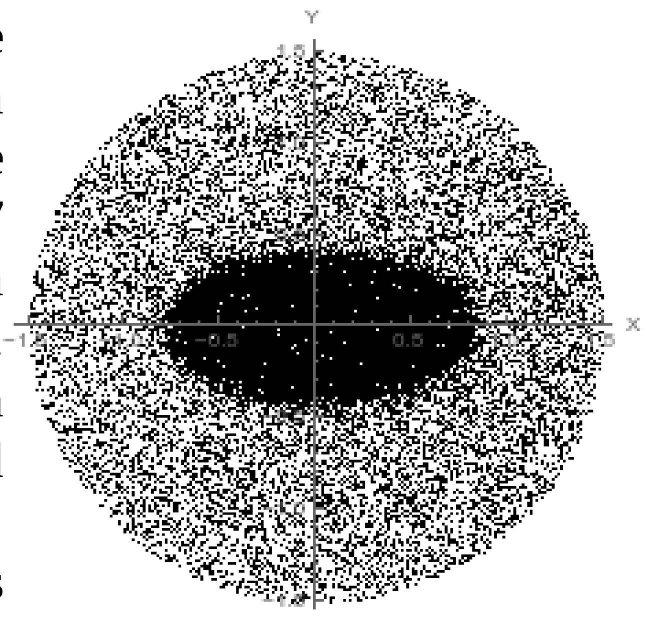

FIG. 6. Visualization of the detection on reflector disk shape.

## DISCUSSION

1. The proposed model of VCN transport in the DND powder is verified via the simulation of the complex experiment.
2. Simulation of the experiment expands the possibilities for the analysis and interpretation of experimental data.
3. The proposed model makes it possible to calculate the reflection coefficient (albedo) of VCNs, the most important characteristic of neutron reflectors, which is not available directly from the described experiment.
4. The models originally developed for Wolfram Mathematica are implemented for Geant4. The performance gain factor is already more than 7 times.

## WHAT ELSE NEEDS TO BE DONE?

1. The VCN reflection from the magnesium foil walls should be taken into account.
2. The weighted Monte Carlo method should be used instead of the direct one.
3. Bragg's diffraction of thermal neutrons on the DND crystal structure might be taken into account.
4. The use of the JINR "Govorun" supercomputer might significantly increase the efficiency of calculations.
5. To simulate extraction systems made of other DND powders or nanomaterials.

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