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Nanodiamond reflectors for an intense source of very cold neutrons: properties and applications

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Workshop on the UCN/VCN source at the INP, Kazakhstan

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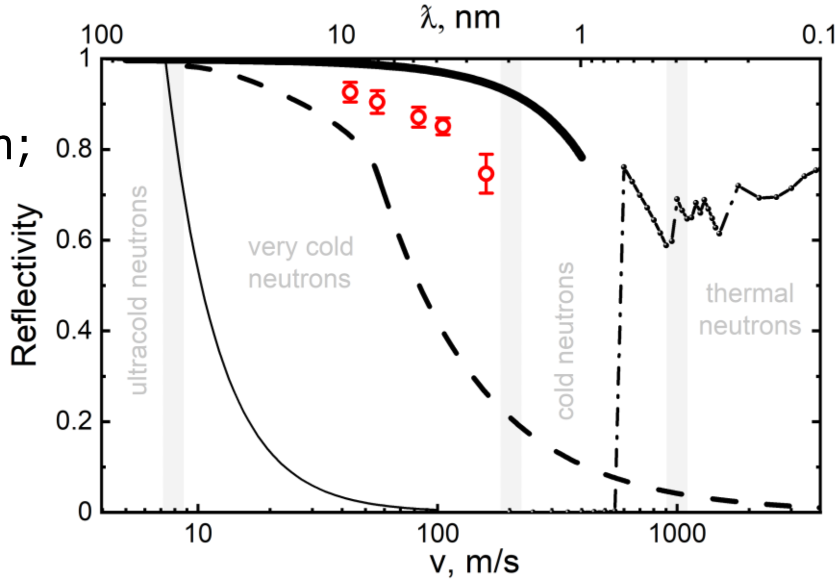
Low energy neutrons: what & why?

Very cold neutrons (VCNs):

- 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.



The reflection probability for isotropic neutrons with different velocities.

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

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

Very cold neutron 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.

Reflectors of very cold neutrons

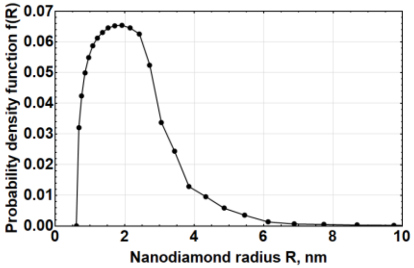
Criteria for the VCN reflector are minimum losses and maximum reflection.
Detonation nanodiamonds (DND) are the perfect candidate!

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

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

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

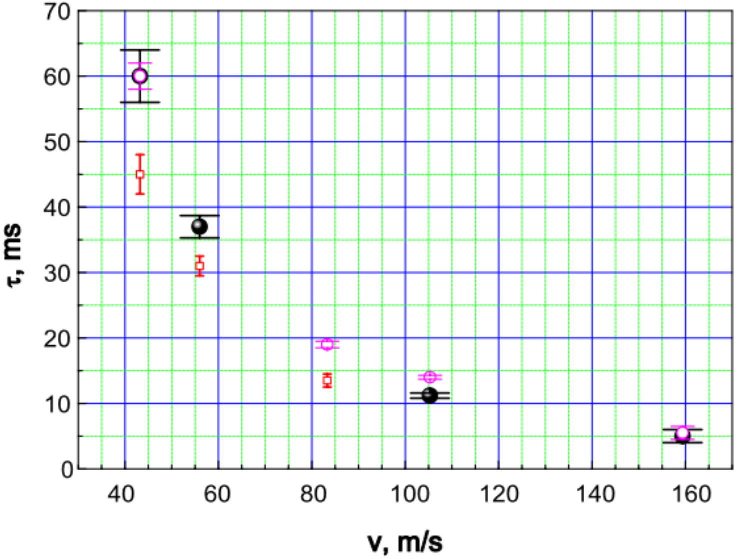
$\boldsymbol{P_{REF} \sim 95\%}$



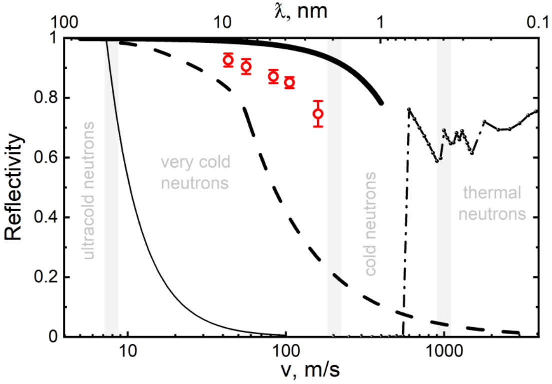
Negative Factors:
~10 at. % of hydrogen,
$\sigma_{abs}^{H} = 0.33\ b;$
$\sigma_{in.sc.}^{H} = 108 \pm 2\ b;$
other impurities
< 0.15 at. %

→ neutron capture
→ neutron activation

VCN storage in a diamond nanopowder trap (2005)



The VCN storages times as a function of their velocity. Black circles correspond to measurements at ambient temperature after 12 hour pumping. Empty circles show measurements at ambient temperature after heating the trap at 120◦C in argon. Boxes indicate results obtained at a temperature of 150◦C under permanent pumping.



The reflection probability for isotropic neutrons with different velocities.

Fluorination: hydrogen substitution in nanodiamonds

the fluorination of DND

$C/H = 7.4 \pm 0.2$ (before)

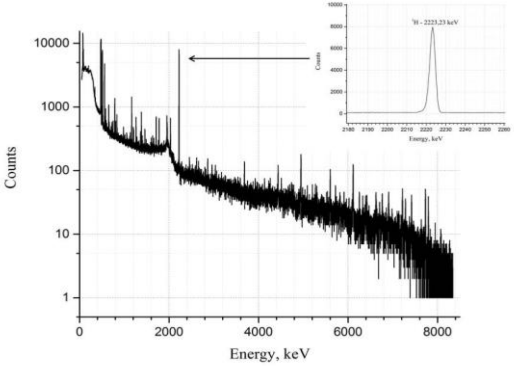
$C/H = 430 \pm 30$ (after)

the additional purification of DND

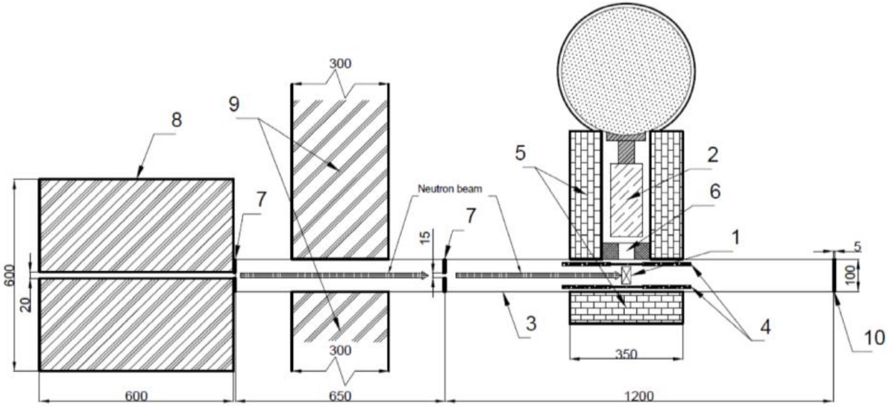
$$\Sigma_{abs}^{after}/\Sigma_{abs}^{before} \approx 0.58$$

$$\Sigma_{abs}^{H} \approx 0.2\Sigma_{abs}^{after}$$

But still significant activation!



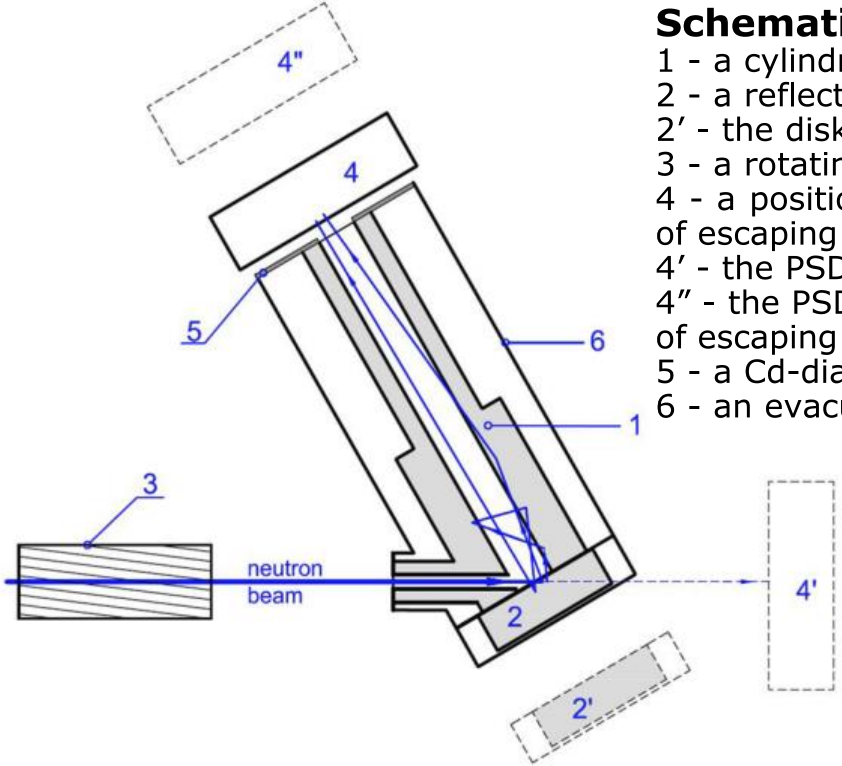
PGNAA set up at the IBR-2



1 - sample; 2 - HPGe detector; 3 - vacuum channel;
4 - protection from LiF; 5 - lead protection;
6 - collimator of gamma quanta;
7 - boron rubber diaphragms;
8 - borated polyethylene collimation assembly;
9 - cadmium-coated polyethylene biological shielding;
10 - neutron beam stop (neutron absorber).

Mass of the samples is about 1 g.

Enhanced directional extraction of VCNs

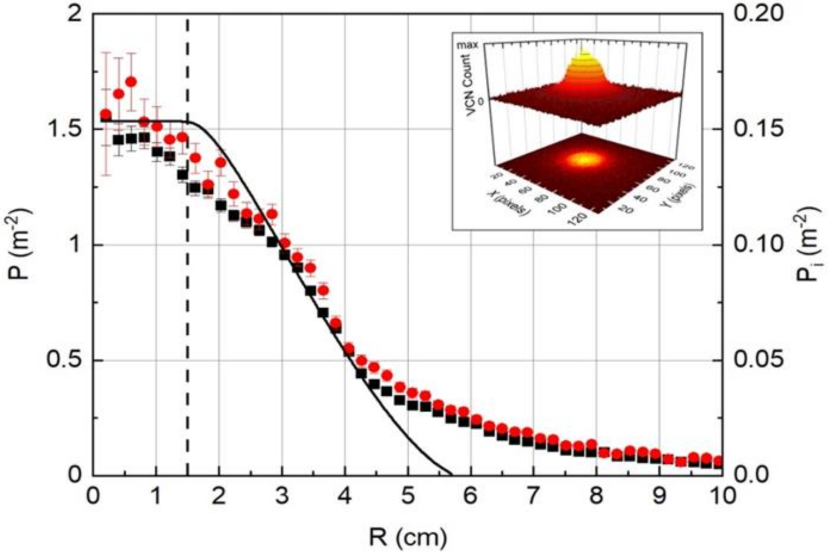


Schematic layout of the experimental setup.

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 of the reflector. →

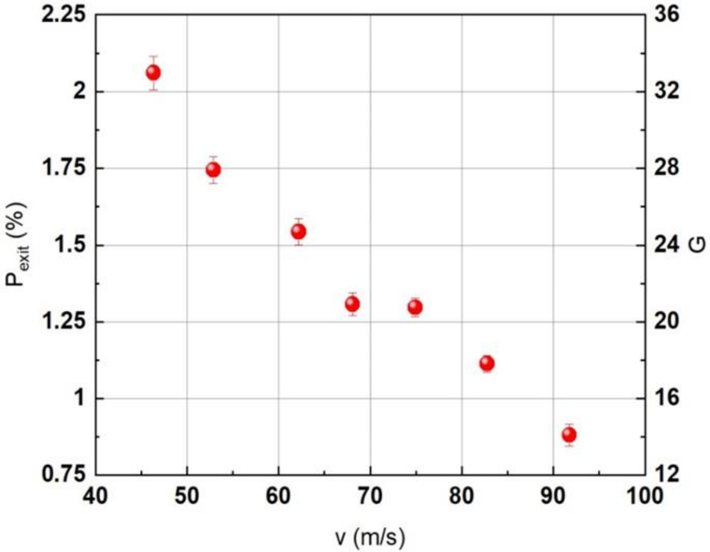
The gain factor for the VCN directional extraction is **~10 times**, and **~30** for the total flux.

Enhanced directional extraction of VCNs



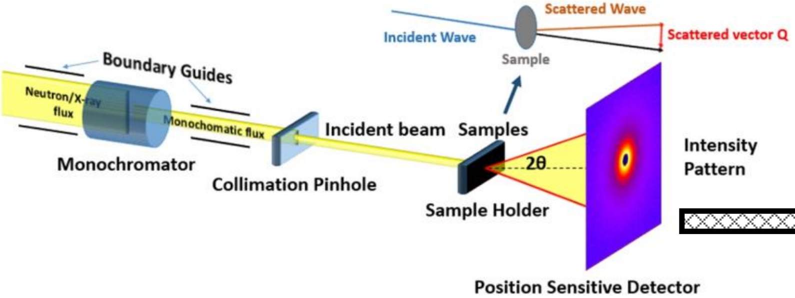
The radial dependence of the specific probability of VCN detection.

Experiments: ● — 57 m/s, ■ — 75 m/s.

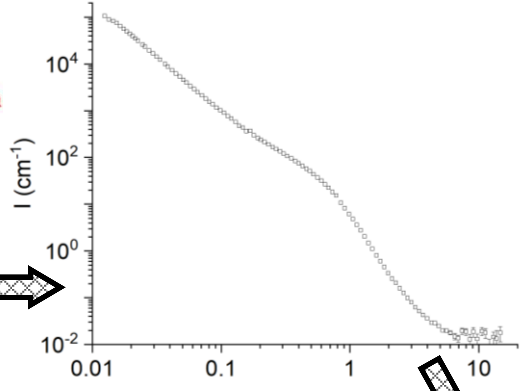


Left axis: the probability of VCN extraction from the reflector.
Right axis: the corresponding gain factor *G*.

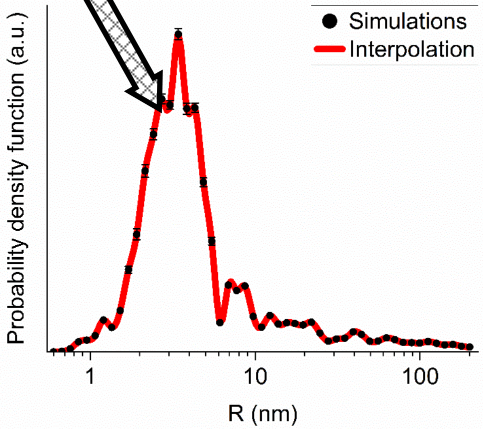
Models of nanopowder structure and neutron transport

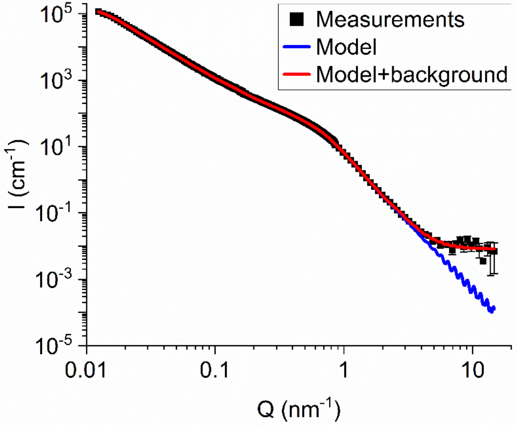


The typical scheme of the SANS experiment.

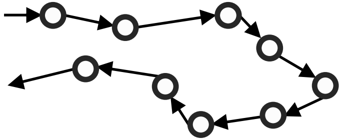


Measured intensity I of scattered neutrons as a function of the transferred momentum Q for the powder of detonation nanodiamonds.

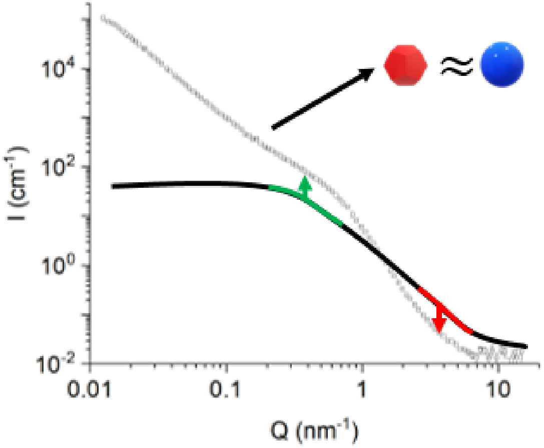




As a result, we have the capability to simulate a multi-scattering process via a single scattering cross-section.



Model’s self-consistency and verification

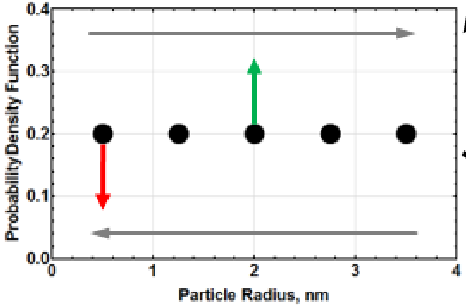


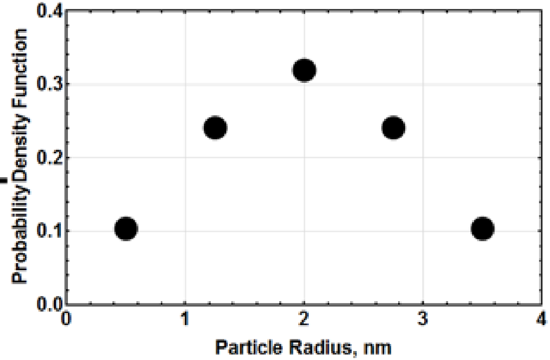
Measured intensity for the DND sample.

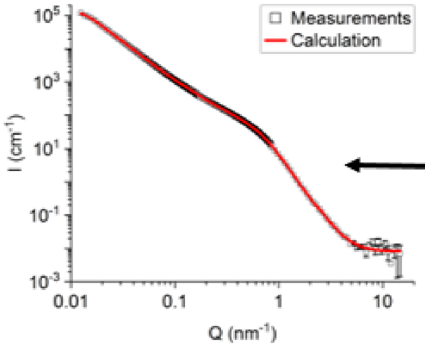
$$I(q) \equiv \frac{d\Sigma_s(q)}{d\Omega} = \int_{r_{min}}^{r_{max}} N \cdot f(r)\, \frac{d\sigma_s(r,q)}{d\Omega}\, dr$$

N – the averaged nanospheres concentration;

f(r) – a fraction distribution of particles with the radius of r.



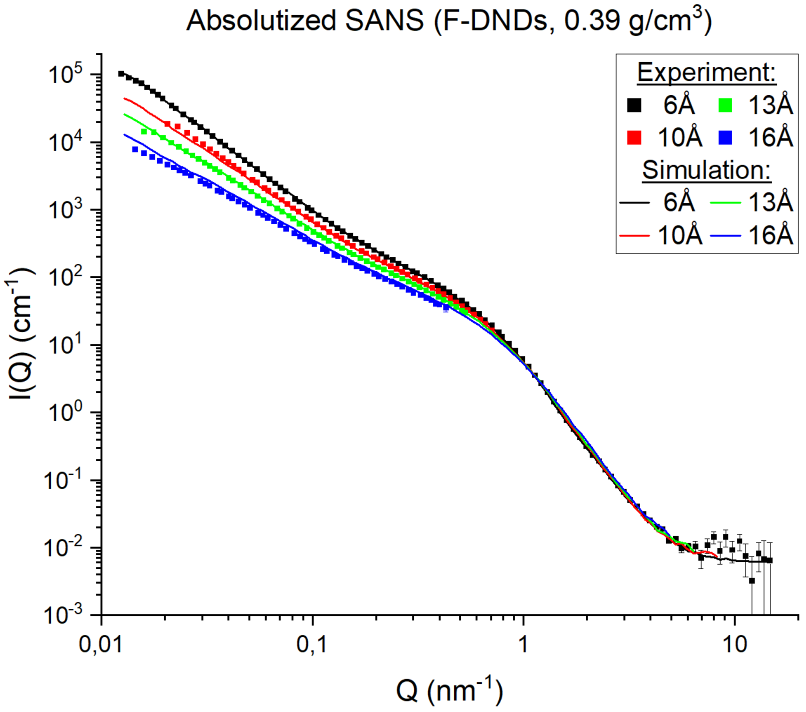


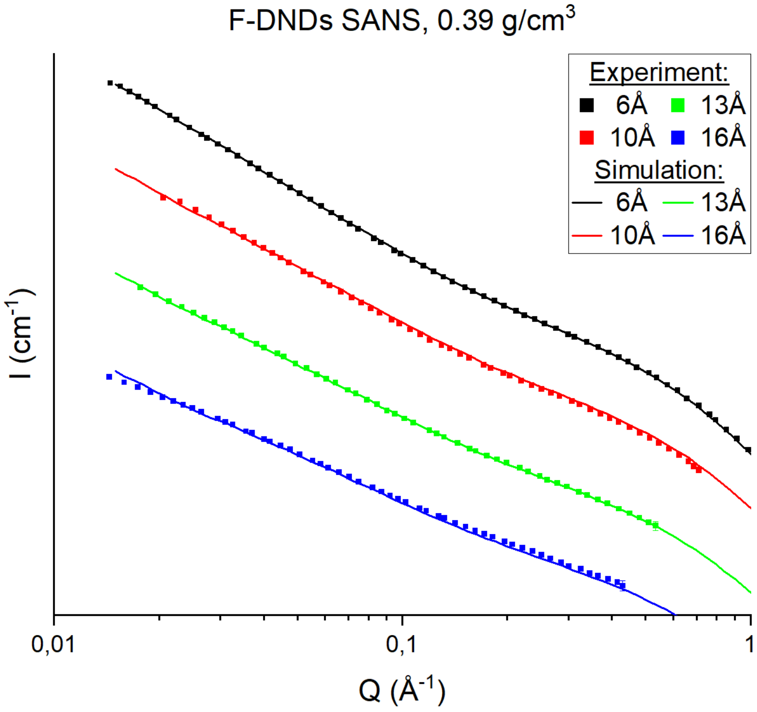


Self-consistency of the model was checked by variation of:

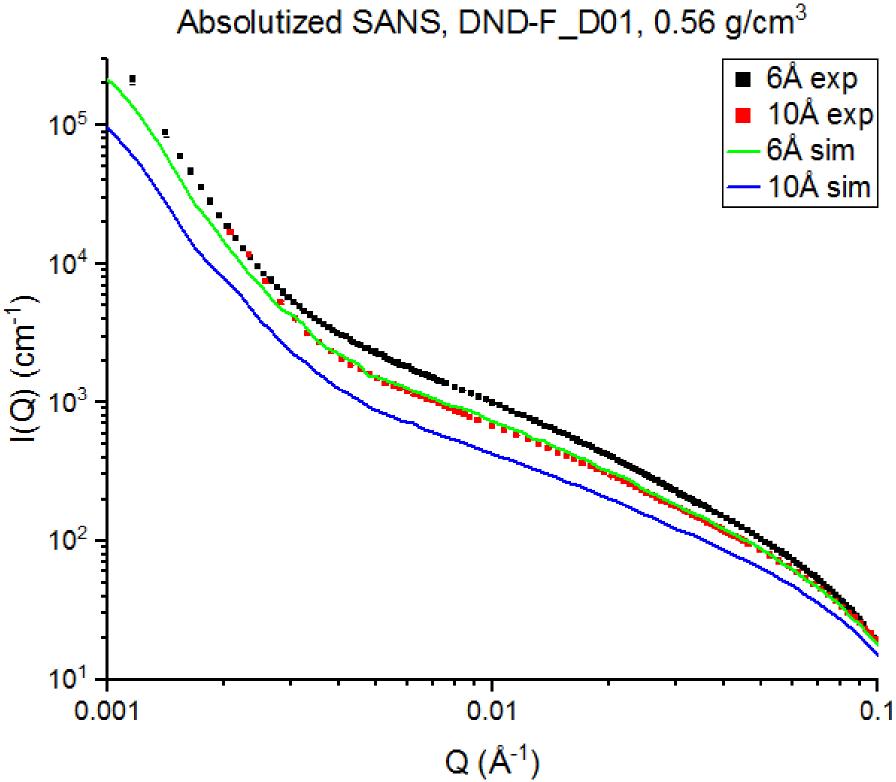
- variance σ of the initial distribution;
- number of discrete points;
- linear/log uniformity scales;
- etc.

Model's self-consistency and verification: Fluorinated nanodiamonds





Model's self-consistency and verification: Deagglomerated fluorinated nanodiamonds



- SANS was measured for a layer thickness of 1 mm.
- The bulk density of ~0.2 g/cm^3 is OK.
- The bulk density of >0.5 g/cm^3 is not OK.

One has to measure

a thinner layer of a nanodiamond powder

OR

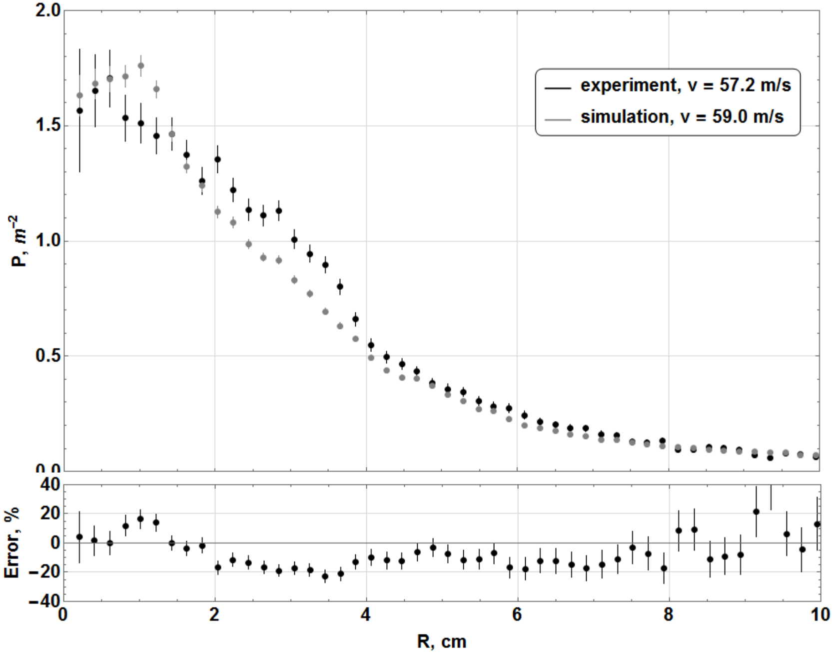
a less denser nanodiamond powder

OR

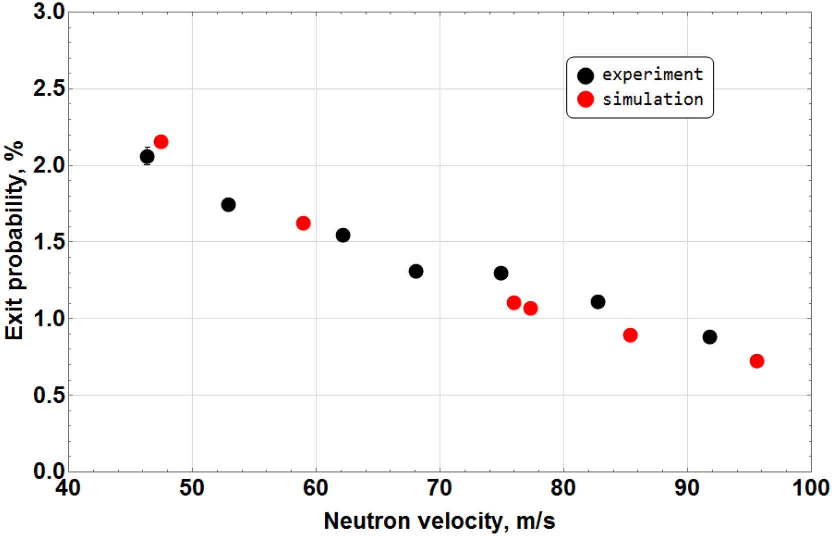
to use a shorter wavelength of neutrons

for development the corresponding model.

Simulation of VCN extraction using nanodiamonds



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



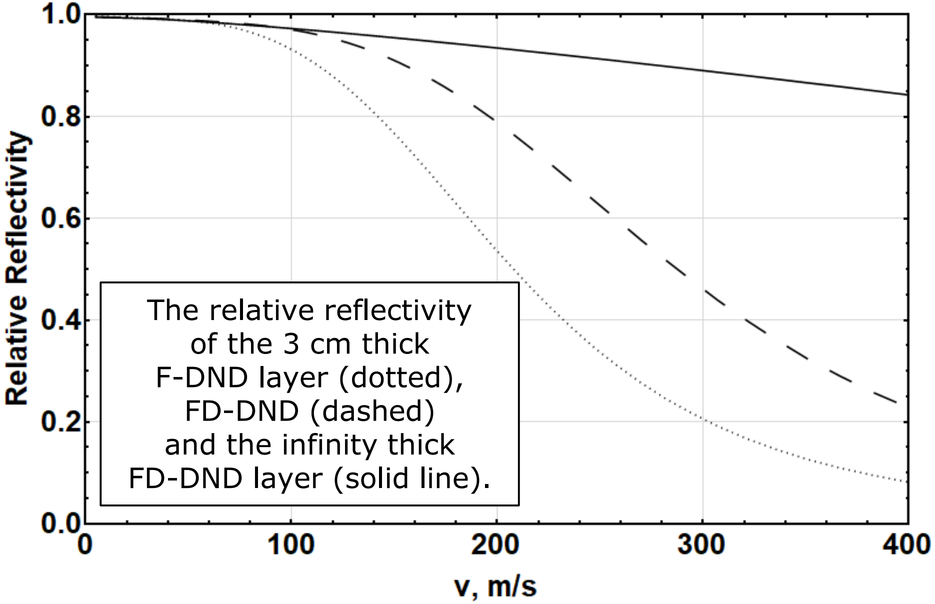
The probability for neutron to escape the reflector through the open end.

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

Deagglomeration: nanoparticle cluster breaking

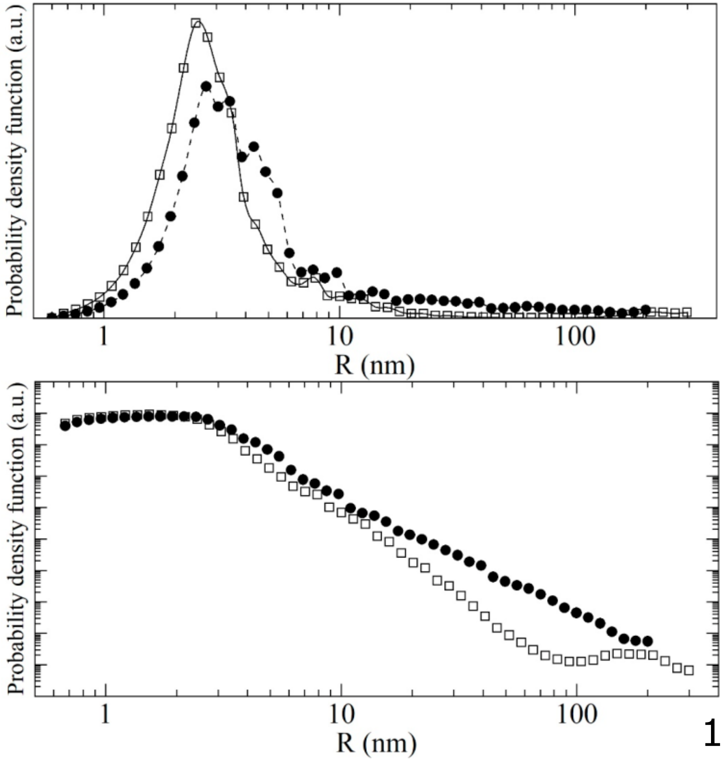
$$P_{REF}^{after}/P_{REF}^{before} \approx 1.10$$

$$\rho_{bulk}^{after}/\rho_{bulk}^{before} \approx 3$$

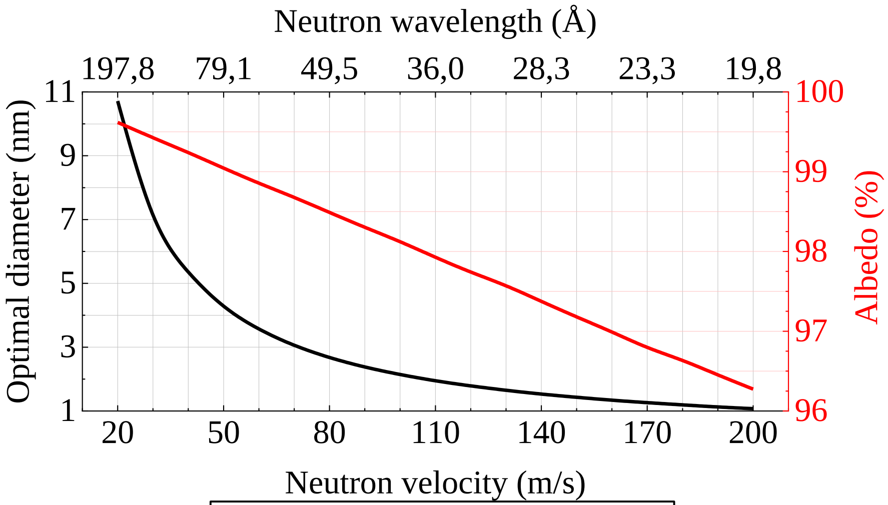


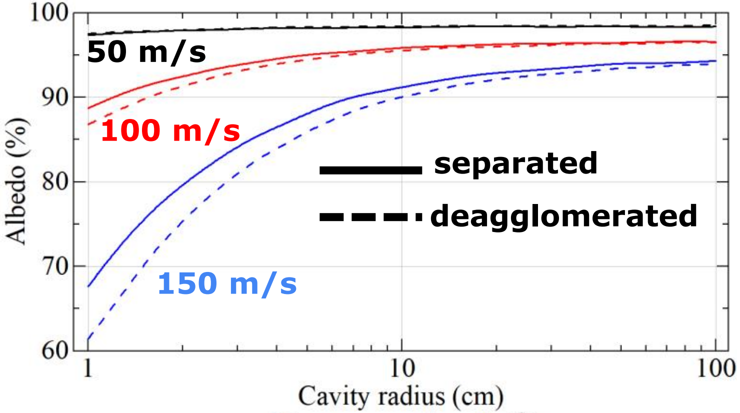
The relative reflectivity of the 3 cm thick F-DND layer (dotted), FD-DND (dashed) and the infinity thick FD-DND layer (solid line).

Size distributions of the fluorinated F-DND (dotted) and the deagglomerated FD-DND (solid).

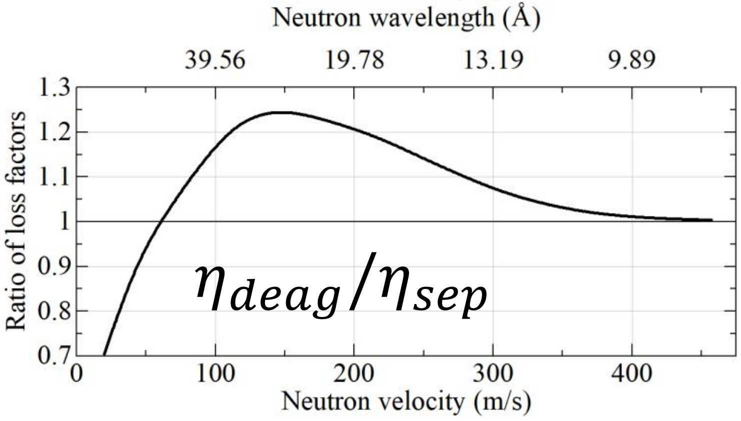


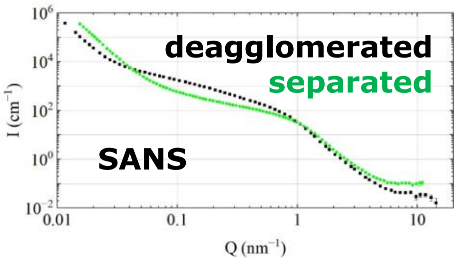
Size separation of nanoparticles

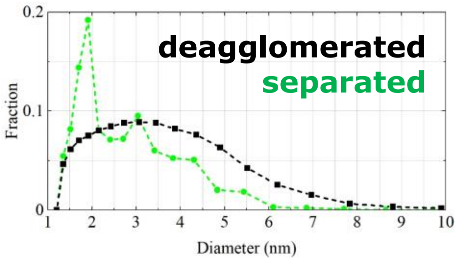




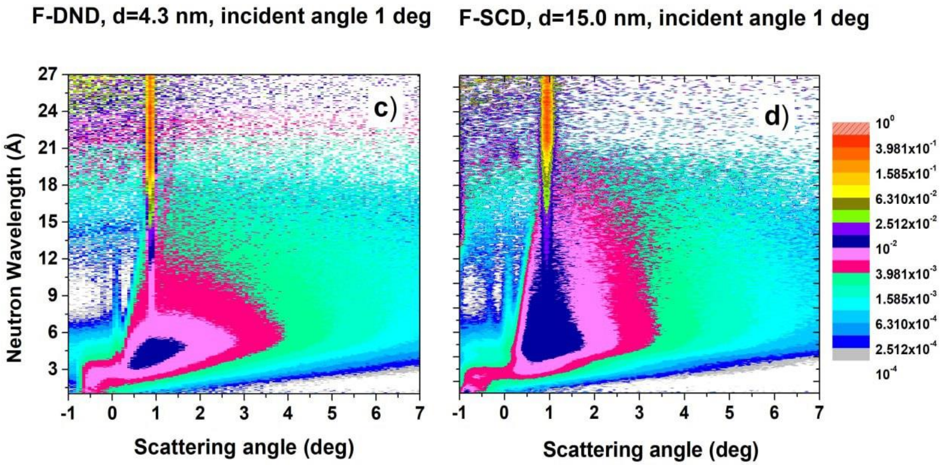
$$P_{REF}^{max}:\ R_{opt} \approx 0.27\lambda$$







Quasi-specular reflection of cold neutrons



Probability of neutron scattering from the surface of ND samples as a function of the neutron wavelength (vertical axis) and the scattering angle in the direction perpendicular to the plane of the sample (horizontal axis).

Nanodiamond sizes in the samples: (c) 4.3 nm; (d) 15 nm.

Tangle of incidence of the neutron beam onto the sample was 1◦.

The effect of the size (**d**) of nanoparticles on the probability of quasi-mirror reflection (**$P_{Q\text{-}S}$**) of neutrons from the surface of diamond nanopowders, and the width of the angular distribution (**Δα**) of reflected neutrons:

- **Cold neutrons (λ>4Å):**
  with increasing **d**, **$P_{Q\text{-}S}$** increases and **Δα** decreases

- **Thermal neutrons (λ<4Å):**
  with increasing **d**, **$P_{Q\text{-}S}$** decreases due to an increase in Bragg scattering.

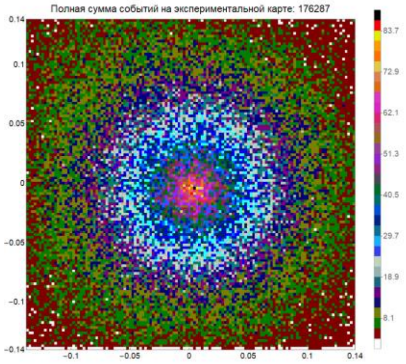
Potential practical applications: SANS

SANS was measured with VCN for nanodiamonds.

$$\boxed{q(\lambda,\theta) = 4\pi/\lambda \sin\theta/2}$$

Systematic difficulties (in our case):

- multiply VCN scattering inside a 250 μm layer;
- large scattering angles;
- therefore, different free paths before being captured inside the detector;
- losses on pathing through the air (non-uniform losses for VCN scattered on a sample at different angles);
- gravity;
- thick detector window made for cold neutrons (4 mm dural);
- monochromatization of the VCN beam
  (not Gaussians spectrums after the velocity selector).



Potential practical applications: neutron EDM

VCN storage in a nanodiamond trap:

- high density of accumulated VCNs;
- VCN's diffuse reflection produces a chaotic neutron gas inside the trap, as in the case of UCN.

$\Delta E = \hbar / t N^{1/2}$ – fundamental constraint on the neutron EDM.

<u>Conditions:</u> a neutron source with the same Maxwell spectrum.

$\tau_{CN} \cong 0.2\ s, E_n = \ 10^{-4}\ eV; \quad \Delta E_{CN}/\Delta E_{UCN} \sim \tau_{UCN} \times {N_{UCN}}^{1/2}/\tau_{CN} \times {N_{CN}}^{1/2}$

$\tau_{UCN} = 10\ s\ \rightarrow \Delta E_{CN}/\Delta E_{UCN} \sim 0.16; \tau_{UCN} = 100\ s\ \rightarrow \Delta E_{CN}/\Delta E_{UCN} \sim 1.6$

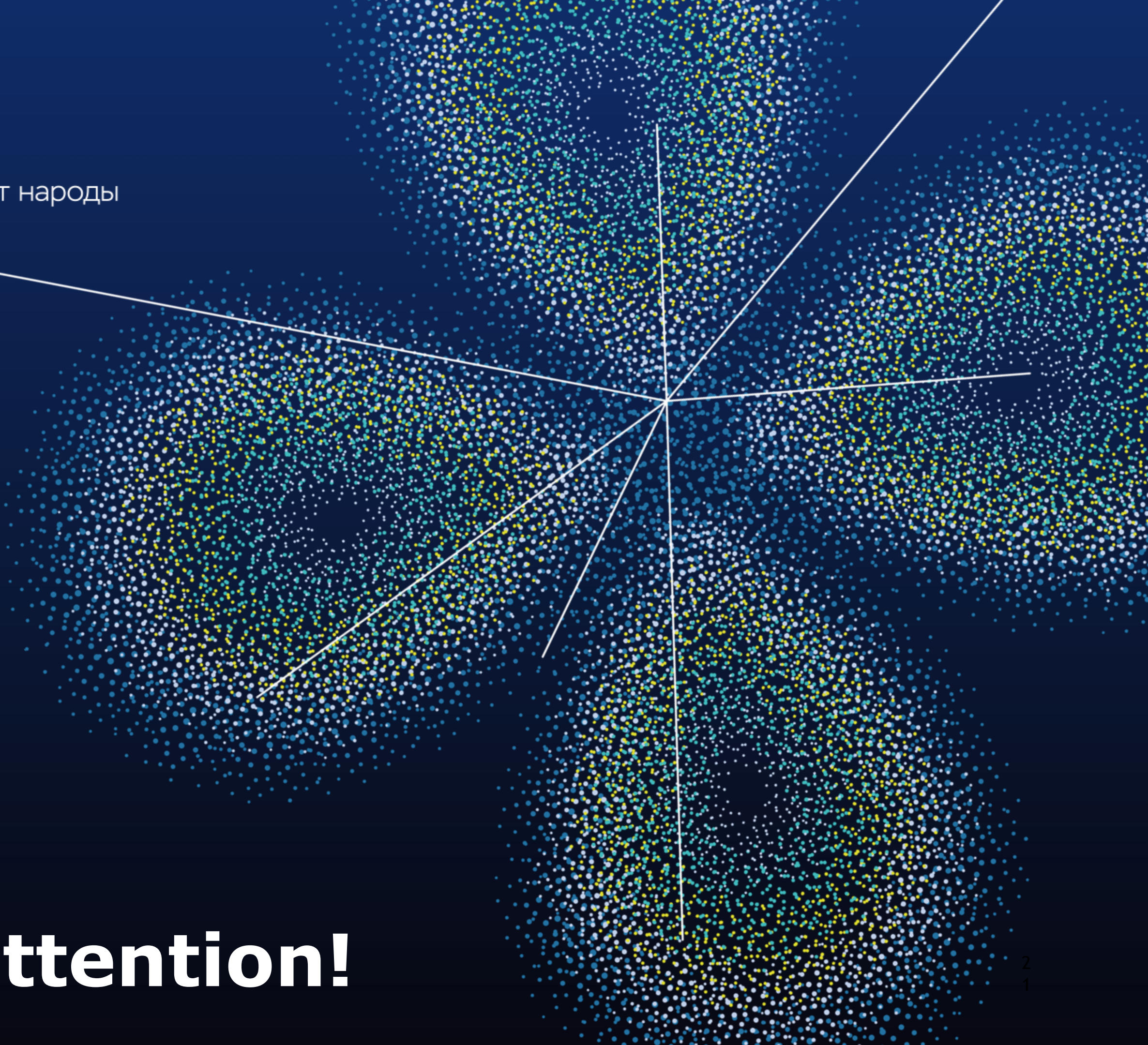
Nanodiamond trap can help to improve the accuracy of neutron EDM search experiments!

Proposal for UCN/VCN source at the INP

- To combine helium VCN and UCN sources.
- To increase the VCN density due to the surrounding the source by a layer of deagglomerated fluorinated nanodiamonds (VCN’s production rate is the same as for UCN due to the uniform distribution in the phase space).
- To use nanodiamonds to extract VCN as well.
- We already have all the instruments and models to make the preliminary and precise simulations.

Future plans

- Optimization of powder density for neutron reflection.
- Study of radiation resistance of fluorinated nanodiamonds.
- Extending the applicability of the transport model to the thermal neutrons by taking into account the crystal structure of nanodiamonds.
- Study of the time dependence of very cold neutron diffusion in a nanodiamond reflector.
- Measurements of directional extraction of very cold neutrons from a reflector made of purified deagglomerated fluorinated nanodiamond powder.



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