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Optimisation of bulk density of nanodispersed medium to maximise its reflectivity for very cold neutrons

Dr Alexander Nezvanov
Frank Laboratory of Neutron Physics, JINR

Ivankov O.I., Lychagin E.V., Nekhaev G.V.,
Nesvizhevsky V.V., Muzychka A.Yu., Turlybekuly K.

ISINN-31, Dongguan, China 29.05.2025

Low energy neutrons: what & why?

Very cold neutrons (VCNs):

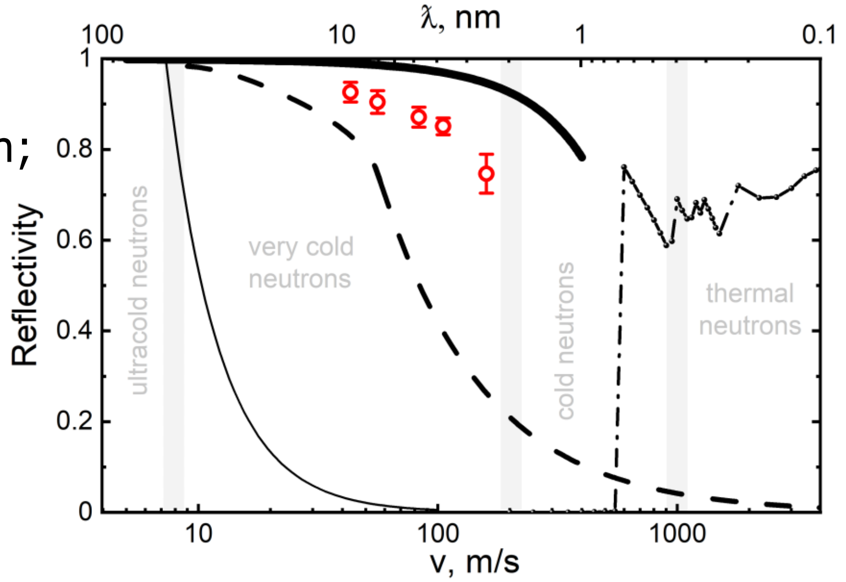
- the typical wavelengths are 2.5–60 nm;
- the velocities are 20–160 m/s;
- the energies are 0.25–130 μeV;
- the temperatures are 3×10^{-3}–1.55 K.

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.
9-10 May 2023, European Spallation Source, Sweden.
8-11 April 2024, Institute of Nuclear Physics, Kazakhstan.



The reflection probability for isotropic neutrons with different velocities.

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.

Neutron techniques:

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

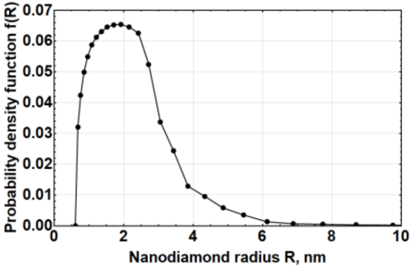
Fundamental Physics:

- 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.

The main disadvantage was a low VCN intensity!

Reflectors of very cold neutrons

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



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

$R_{opt}(\lambda) \approx 0.7 - 4.3\ nm,$
$\lambda \in [26, 160]$ Å

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

Implemented solutions:

the fluorination of DND (*PGNAA*)

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

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

the additional purification of DND (*NAA*)

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

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

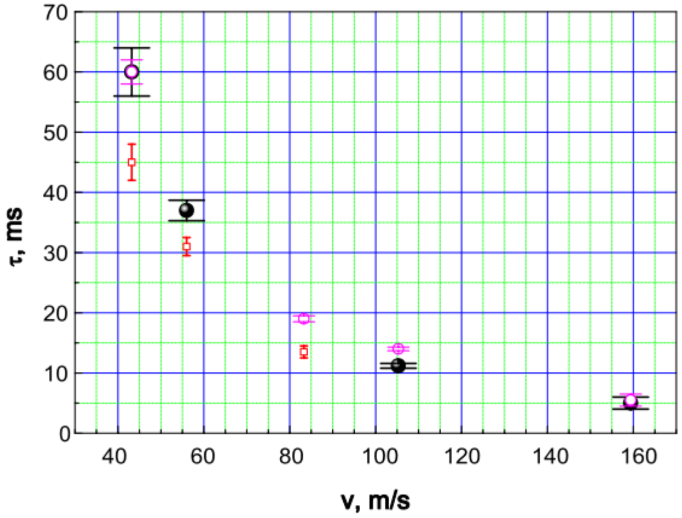
But still significant activation!

the deagglomeration of DND (*SANS*)

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

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

VCN storage in a diamond nanopowder trap (2005)

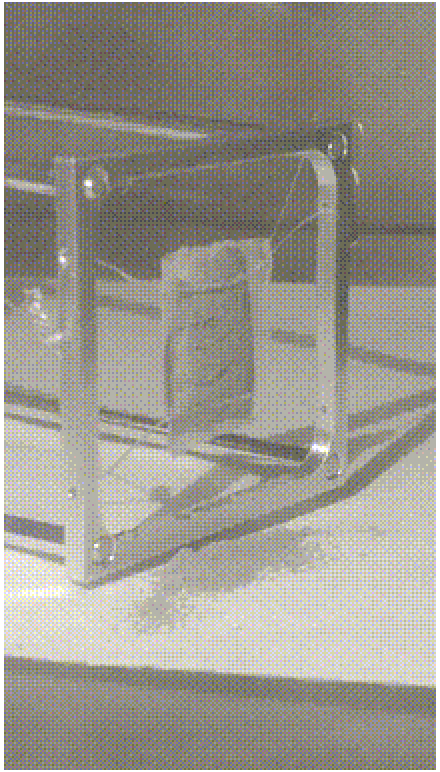


The VCN storages times vs VCN velocity

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.
Red boxes indicate results obtained at a temperature of 150◦C under permanent pumping.

✗ ~~Neutron Lifetime~~

✓ Neutron EDM



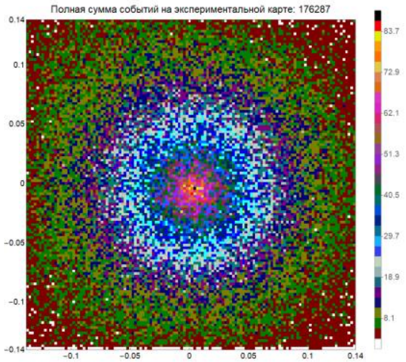
Potential practical applications: SANS

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).



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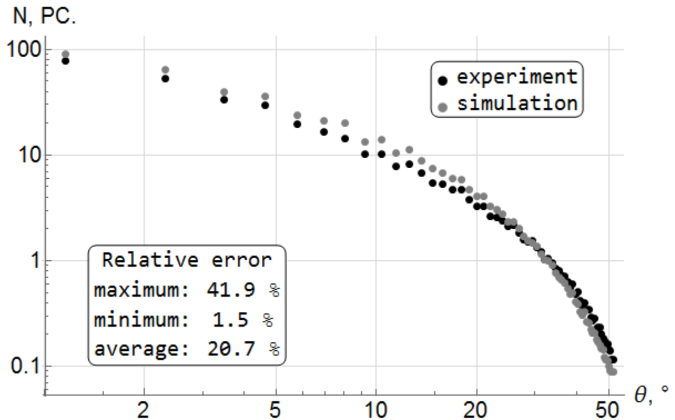
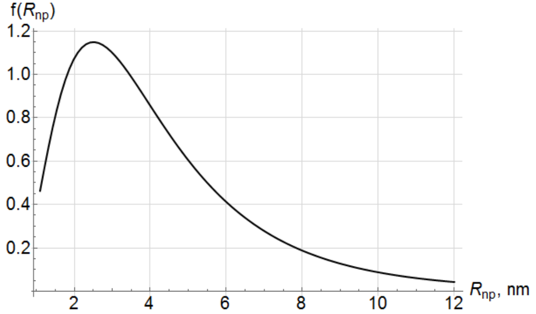
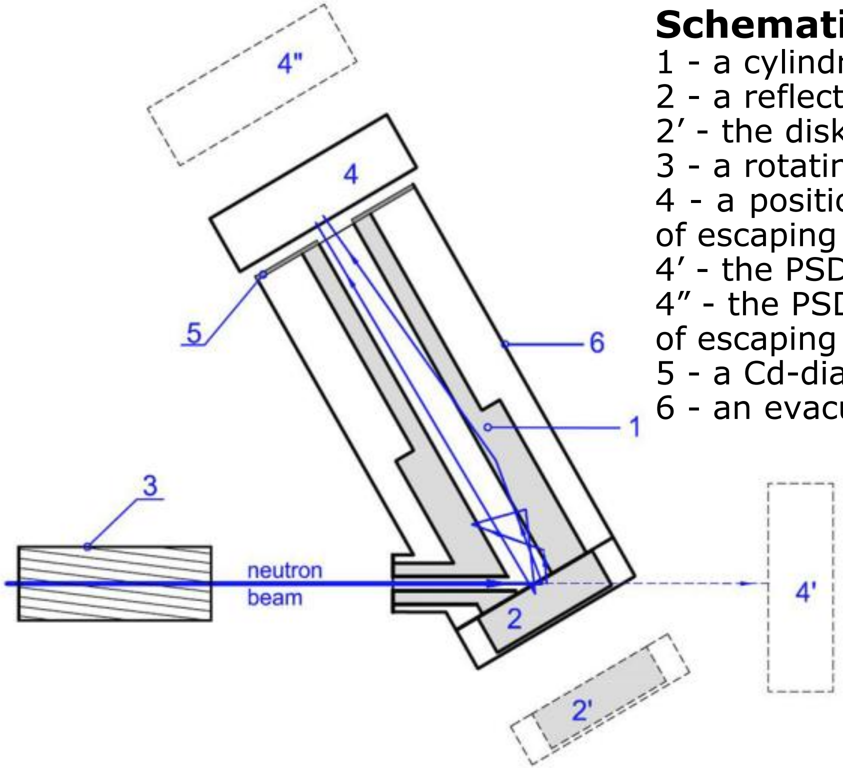


Nanodiamonds size distribution



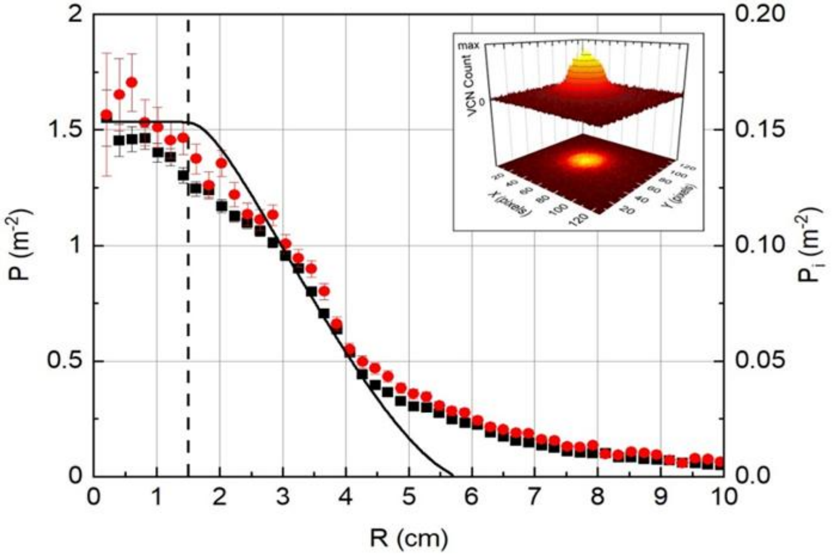
Enhanced directional extraction of VCNs



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.

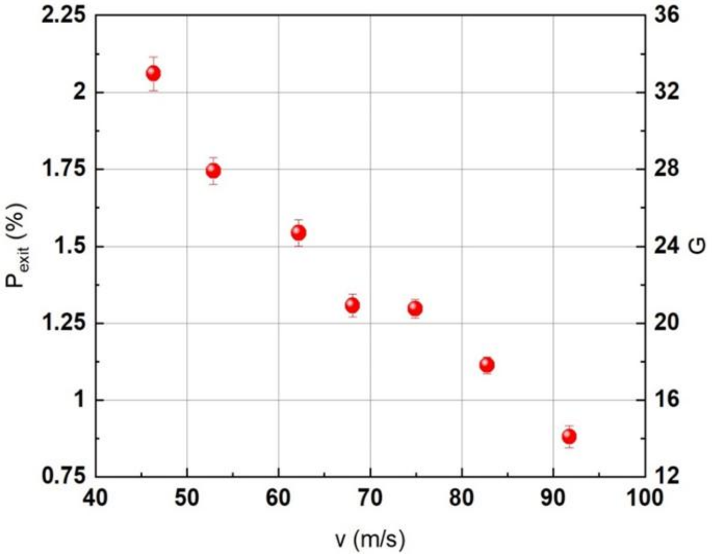
The gain factor for the VCN directional extraction is **~10 times**, and **~30** for the total flux.

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*.

Proposal for UCN/VCN source at the INP

- To combine helium VCN and UCN sources (ALSUN project).
- 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.

Neutron Transport Equation

Artem'ev V.A. // Vopr. At. Nauk. Tekh., Ser. Fiz. Yad. Reakt., Vol. 1–2, P. 7–12 (2003).

$$\frac{1}{v_{eff}}\cdot\frac{\partial\varphi}{\partial t} = -\mathbf{\Omega}\nabla\varphi - \Sigma_t\varphi + \int d\mathbf{\Omega}'\varphi(\mathbf{r},\mathbf{\Omega}',t)\Big[\Sigma_s W_s(\mathbf{\Omega}'\to\mathbf{\Omega}) + \Sigma_{coh}^{(m)}W_{coh}^{(m)}(\mathbf{\Omega}'\to\mathbf{\Omega}) + \Sigma_{coh}^{(p)}W_{coh}^{(p)}(\mathbf{\Omega}'\to\mathbf{\Omega})\Big] + q(\mathbf{r},\mathbf{\Omega},t)$$

Total cross-section
=
scattering + losses

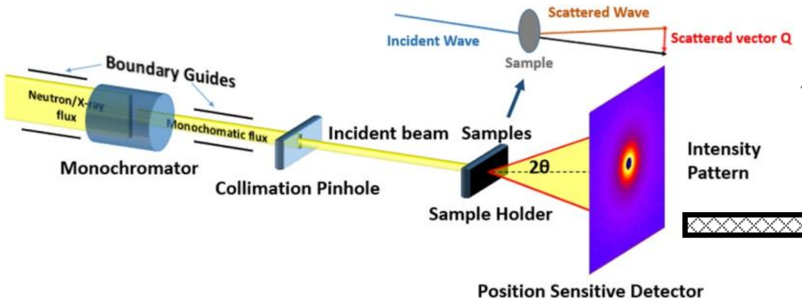
Equation Solutions

The diffusion approximation [1]

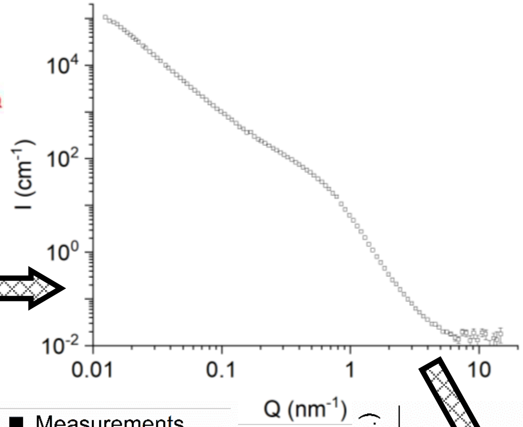
The Monte Carlo method

The approximation of small scattering angles [2]

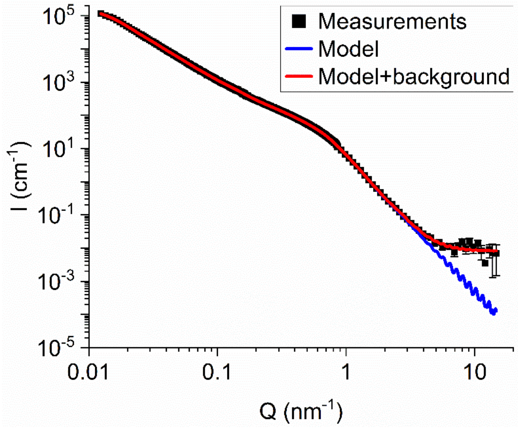
Models of nanopowder structure and neutron transport

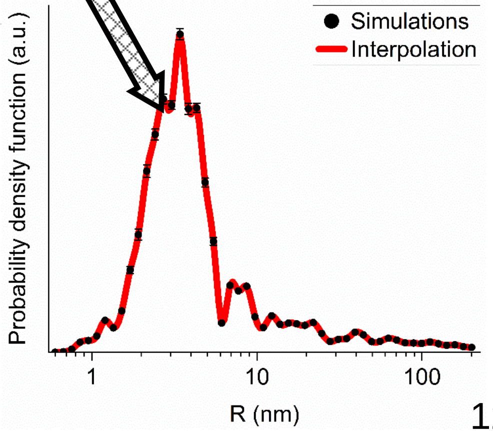


The typical scheme of the SANS experiment.

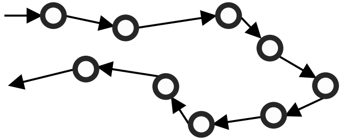


Measured intensity I of scattered neutrons as a function of the transferred momentum Q for the nanodiamond powder.

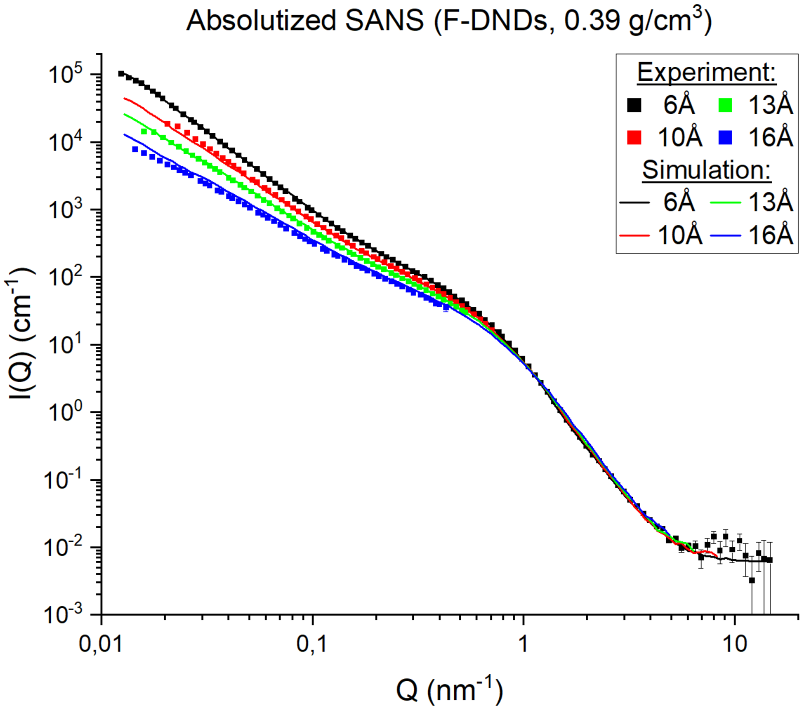


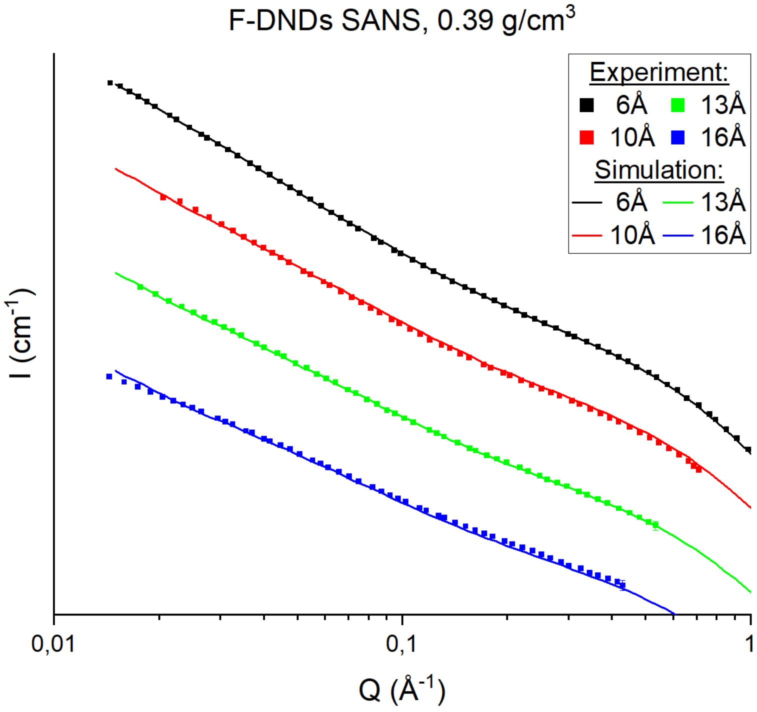


<u>As a result, we have the capability to simulate a multi-scattering process via a single scattering cross-section.</u>

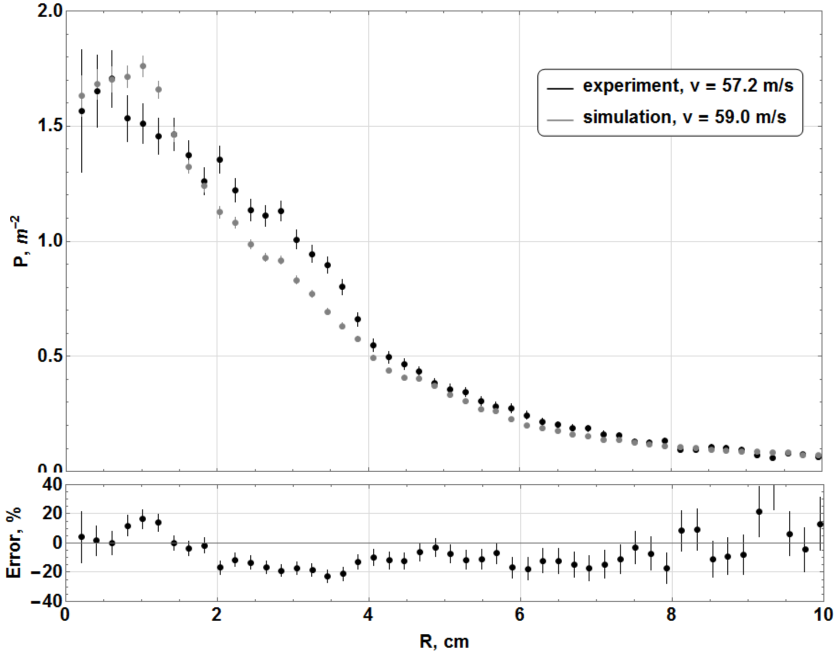


Model’s self-consistency and verification: Fluorinated nanodiamonds

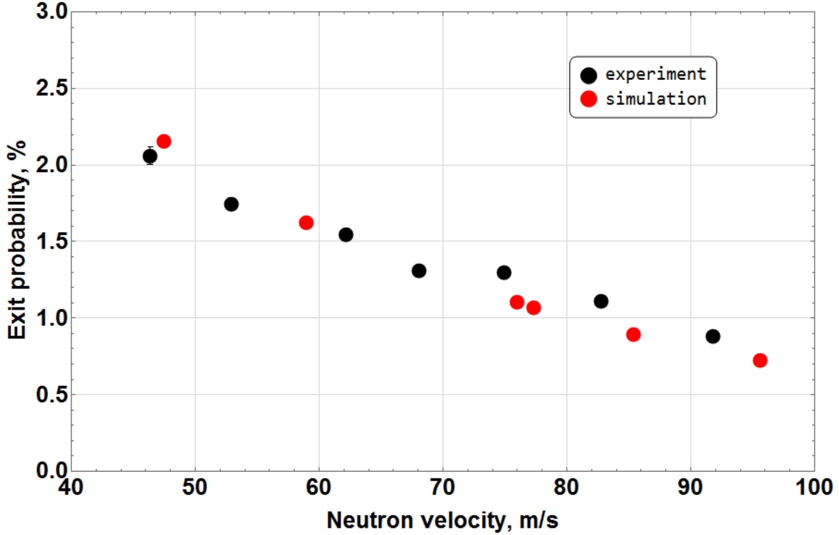




Simulation of VCN extraction using nanodiamonds



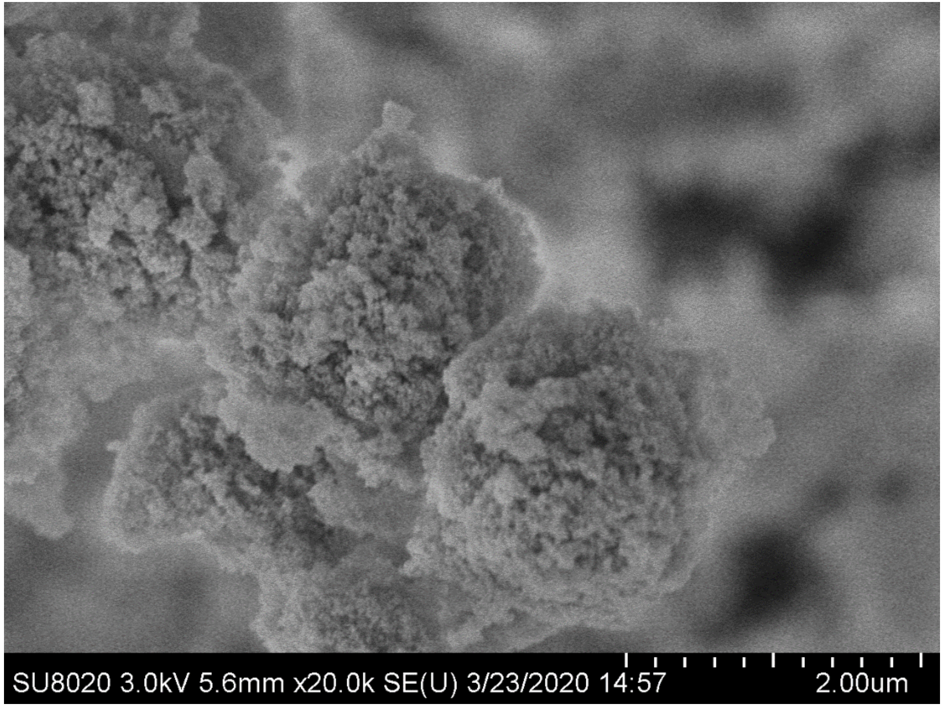
The radial dependence of the specific probability of very cold neutron detection.



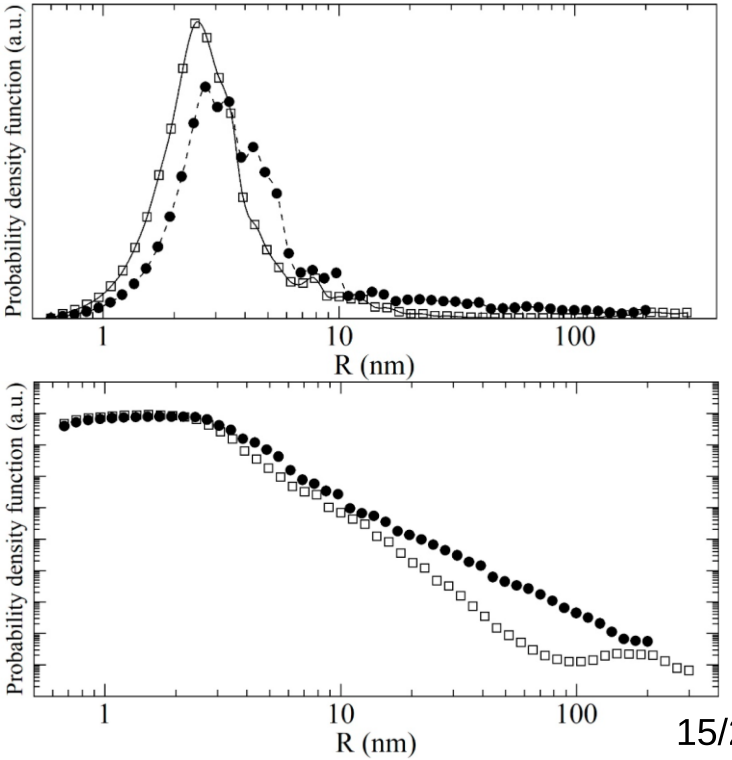
The probability for neutron to escape the reflector through the open end.

The model gives us the opportunity to calculate the reflection coefficient (albedo), as well as to analyse the powder structure.

Deagglomeration: nanoparticle cluster breaking



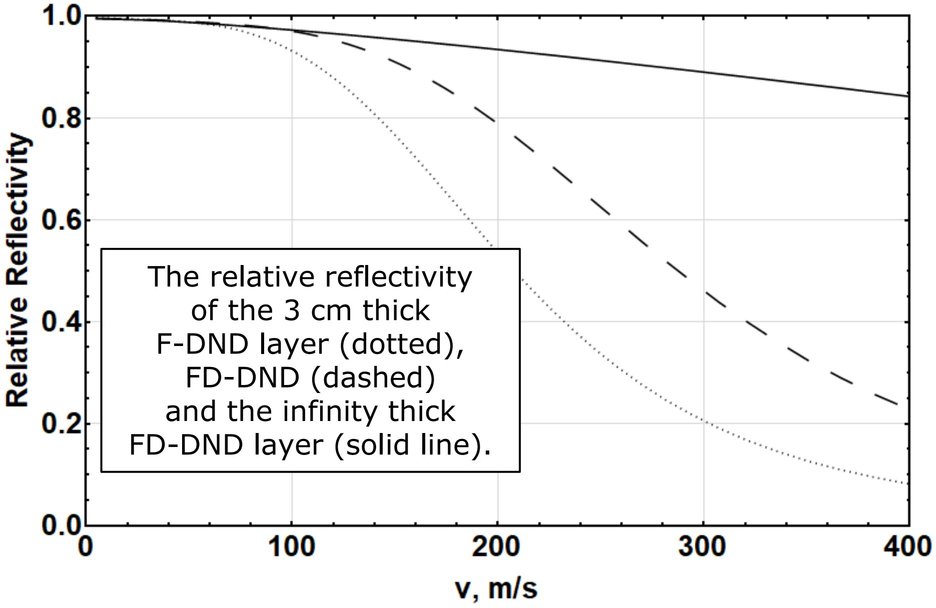
Size distributions of the fluorinated F-DND (dotted) and the deagglomerated FD-DND (solid).



Deagglomeration: nanoparticle cluster breaking

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

$$\rho_{bulk}^{after}/\rho_{bulk}^{before} \approx 3, \text{ from 0.3 to 0.9 } g/cm^3$$



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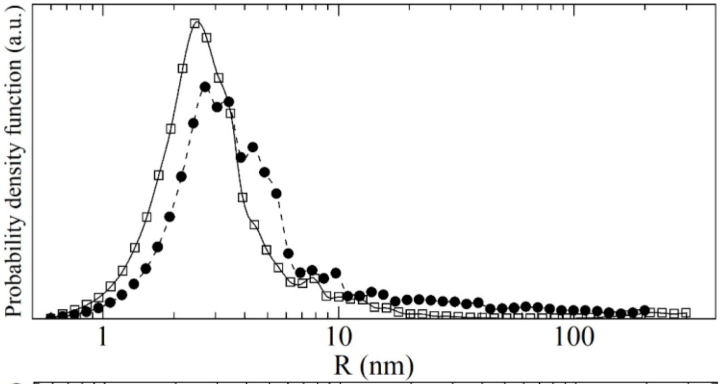
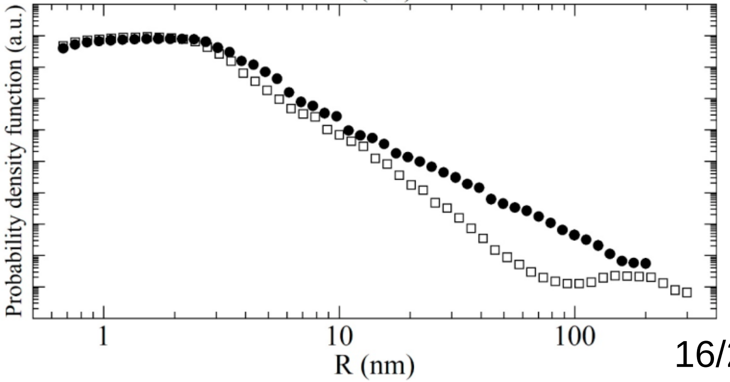
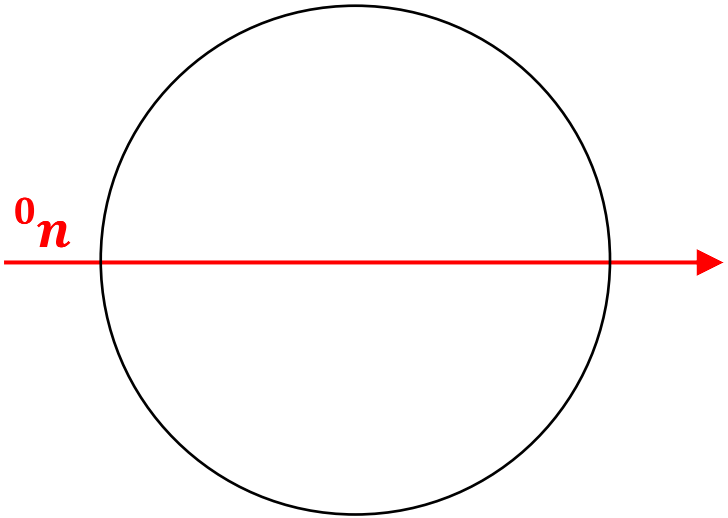
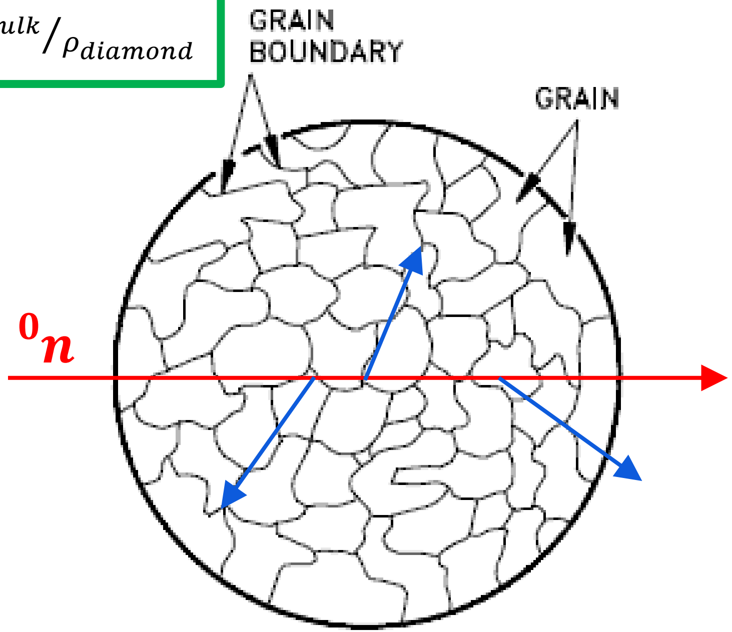




Optimisation of bulk density of nanopowder

The packing coefficient $\gamma = {}^{V_{medium}}/_{V} \equiv {}^{\rho_{bulk}}/_{\rho_{diamond}}$





$\boldsymbol{\gamma = 0}$ is no medium at all
(neutron reflection is 0)

$\boldsymbol{\gamma = 1}$ is no pores or nanoparticles at all
(neutron reflection is close to 0)

Optimisation of bulk density of nanopowder

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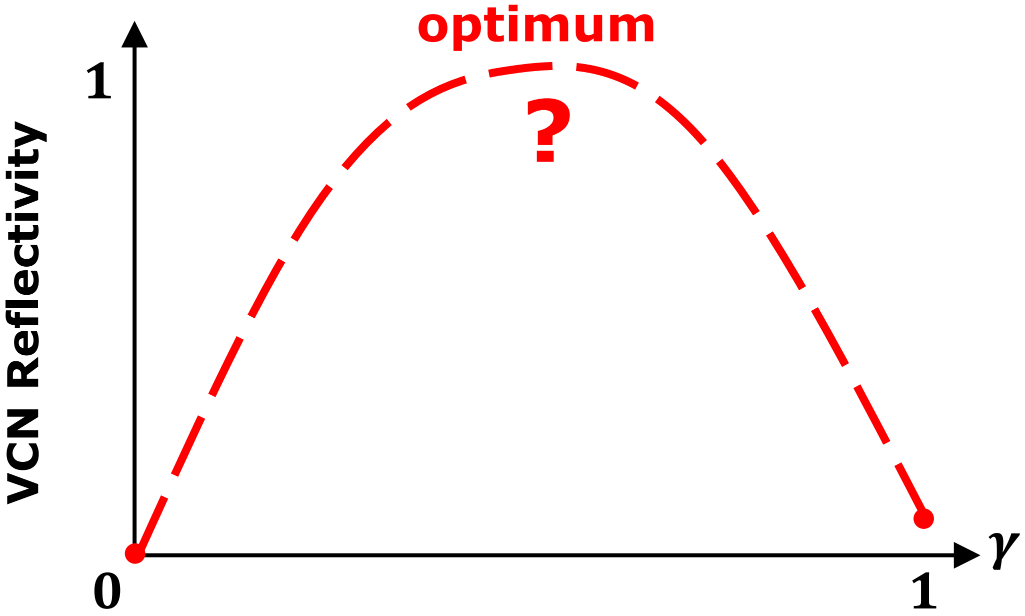


“Structural” interpretation of the effect

Higher closing packing causes the aggregation of nanoparticles, creating larger coherent scattering volumes.

Scattering on these volumes is predominantly forward scattering.

“Effective potential” interpretation of the effect

Diffusive reflectivity ***R*** is determined by the ratio:

$$\boldsymbol{R = {}^{\sigma_{tr}}/_{\sigma_a}}$$

Here $\boldsymbol{\sigma_{tr}}$ is a transport cross-section, and $\boldsymbol{\sigma_a}$ is capture cross-section (losses).

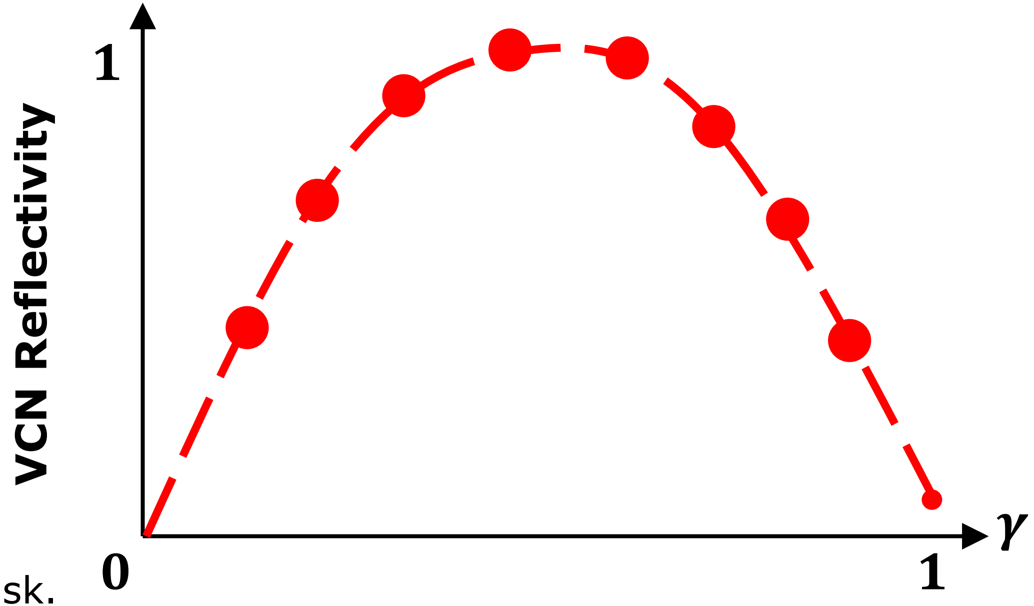
Therefore, small-angle scattering can be neglected.

In this case, the effect is similar to **the appearance of the optical potential** for UCNs.

$$\boldsymbol{U_{opt} = \frac{4\pi\hbar^2}{2m} n b_{coh}}\ , \quad \boldsymbol{U_{diamond} \approx 305\, neV,} \quad \boldsymbol{U_{eff} = \gamma \cdot U_{opt} \approx 35 - 80\, neV}$$

Measurement Option #1

Take direct VCN reflectivity measurements of samples with various bulk densities.



Difficulties:

1. One VCN source is operating.
2. Measurement of VCN albedo from a flat sample is a complicated task.

Measurement Option #2

Measure neutron transmittance instead of reflectivity.

In other words, to measure a total cross-section of neutrons.

Positive factors:

1. For CN and VCN, the total cross-section for nanodiamonds should only be determined by neutron capture and elastic coherent cross-sections.
2. It is well known how these cross-sections depend on the neutron wavelength.

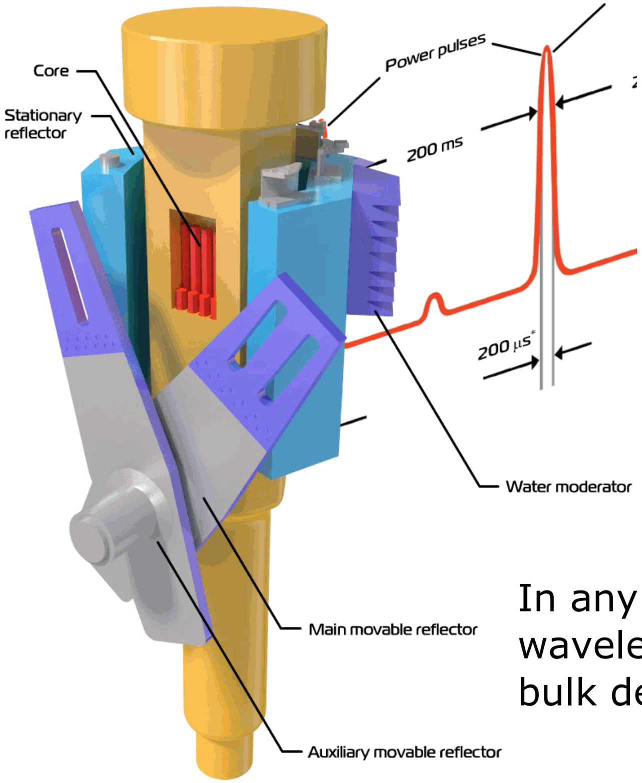
Measurement Option #3

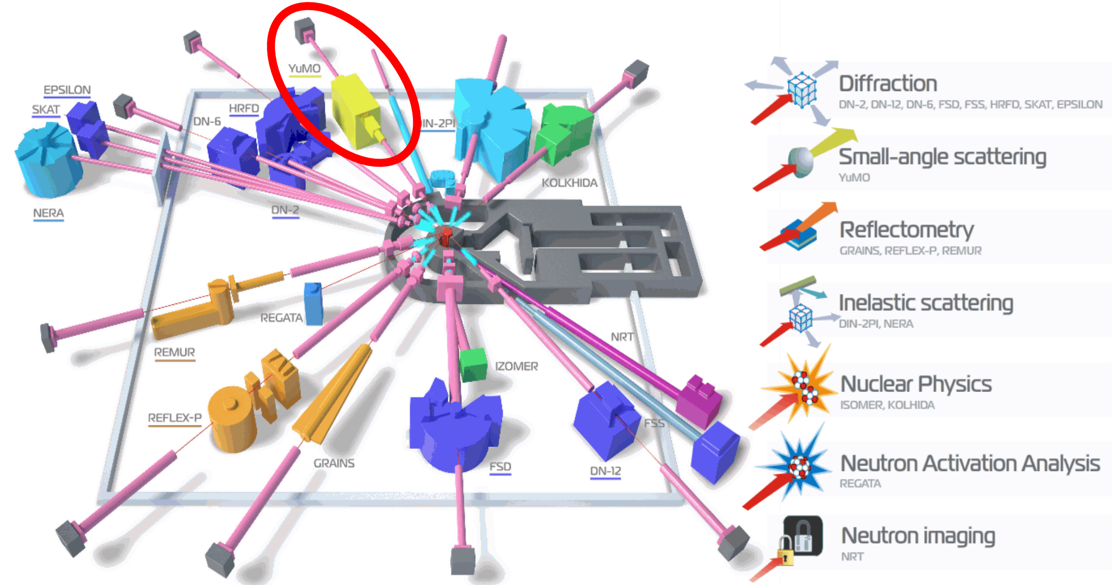
Measure small angle neutron scattering (SANS).

Even more positive factors:

1. SANS intensity $\boldsymbol{I(q) = d\Sigma/dq}$ is a differential macroscopic cross-section of a single elastic coherent neutron scattering, which defines the reflectivity.
2. At the same time, the standard SANS facilities can also be used to measure neutron transmittance directly.

YuMO SANS Facility at the IBR-2

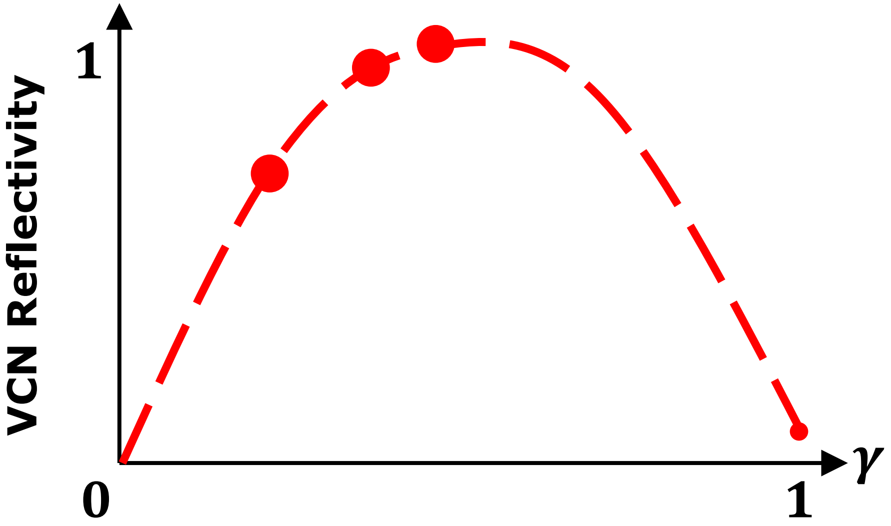




In any case, the density effect should not depend on the neutron wavelength, which means that we can try to find the optimal bulk density on a standard facility. **We have chosen SANS.**

What have we done

- The close packed samples with γ of 0.25, 0.40, and 0.47 were prepared.
- Bulk samples of **various thicknesses** and **masses** equal to the packed ones were prepared.
- The SANS was measured for both, the close packed and bulk samples.



Long Story Short...

“*... the first step is always the hardest”.* – The First Step Makers.

We have faced with several issues:

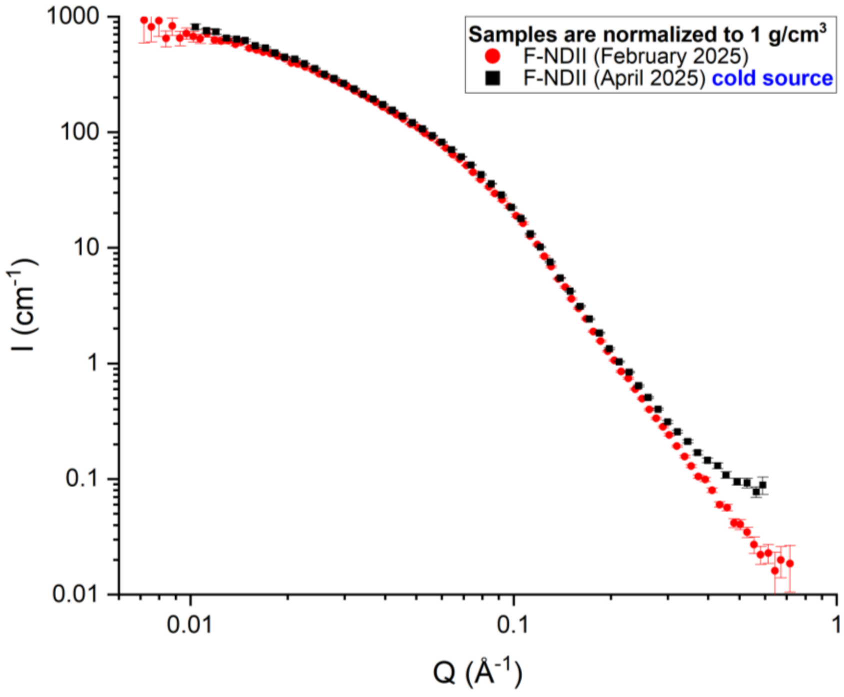
1. There are difficulties with preparing samples with higher bulk densities:
    - Limited sample density achievable by pressing.
    - Deformation of a press mold being used.
2. Since only dense samples of small sizes can be obtained on a press:
    - SANS statistics is low.
    - Neutron transmittance can not be measured correctly since the collimator size is larger than a sample.

Long Story Short...

More issues related to the YuMO SANS:

3. The minimum available transferred momentum ***q*** at the YuMO facility is insufficient. VSANS is preferred.

4. The series of measurements of samples with various densities and thicknesses of equal masses were done during different modes of YuMO work:
with **thermal** and **cold** neutron moderators



(No) Conclusions

We can’t compare the existing experimental data or draw conclusions from it.

Future plans:

— To use different fillers to achieve higher nanopowder densities on a press.

— To develop a new press mold made of hardened steel.

— To remeasure SANS with using additional samples with higher bulk density and corresponding initial bulk density but with equal mass (thicker).

— To use the same neutron spectrum (moderator) for both measurements.

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Gracias
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Благодаря
Спасибо
Thank you
Multumesc
Grazie
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شكرًا جزيلاً
Gracias
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Хвала
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