JINR
JOINT INSTITUTE
FOR NUCLEAR RESEARCH

Study of the properties and applications of nanodiamond reflectors of low-energy neutrons

A. Nezvanov

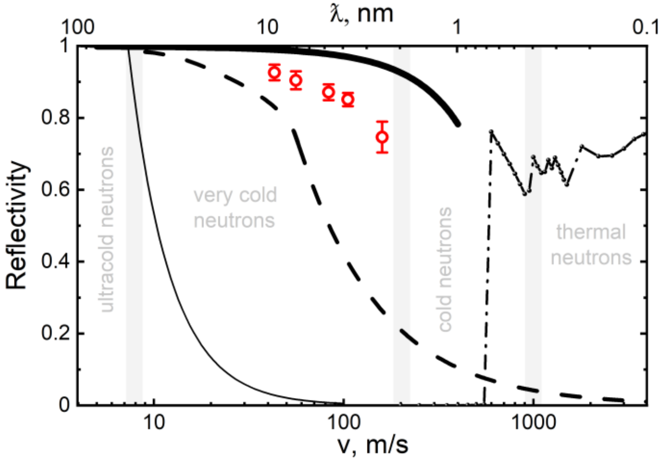
58th meeting of the PAC for Nuclear Physics

Low energy neutrons: what & why?

Ultracold Neutrons
(~4 m/s)

Cold Neutrons
(~500 m/s)

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.



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.

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

Neutron techniques:

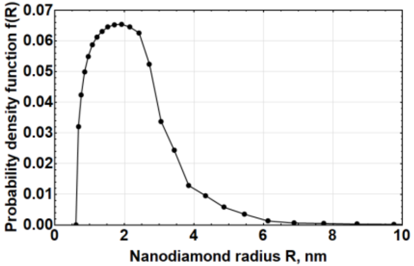
- SANS;
- spin-echo;
- TOF spectroscopy, in particular, high-resolution inelastic scattering;
- reflectometry, diffraction, microscopy, holography, tomography, etc.

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.

Reflectors of very cold neutrons

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



Positive Factors:

size distribution;

$R_{opt}(\lambda_{VCN}) \approx 0.7 - 4.3\ nm$;

$b_{c.sc.}^{C} = 6.65\ fm$;

$\sigma_{c.sc.}^{C} = 5.55\ b$;

$\sigma_{abs}^{C} = 3.5\ mb$;

$\sigma_{in.sc.}^{C} \rightarrow 0\ (T \rightarrow 0)$;

$\rho^{Diamond} \approx 3.5\ g/cm^3$.

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

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

Fluorination: hydrogen substitution in nanodiamonds

the fluorination of DND

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

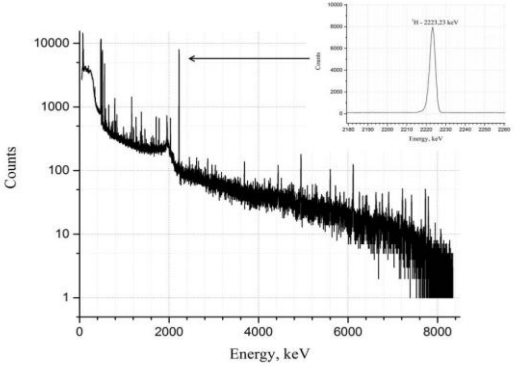
$C/H = 430 \pm 30$ (after)

the additional purification of DND

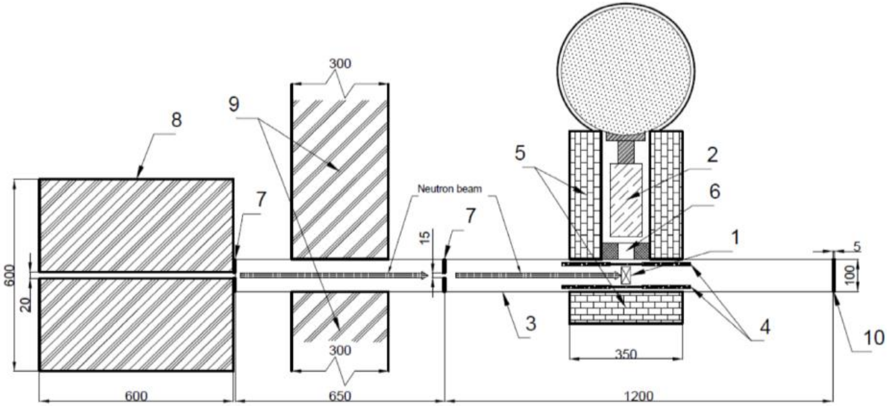
$$\Sigma_{abs}^{after}/\Sigma_{abs}^{before} \approx 0.58$$

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

But still significant activation!



PGNAA set up at the IBR-2

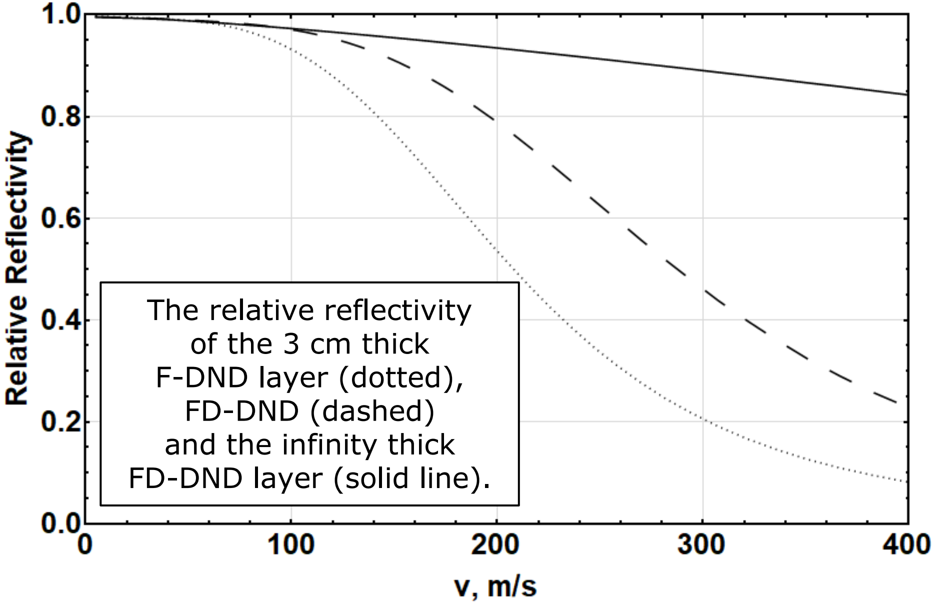


1 - sample; 2 - HPGe detector; 3 - vacuum channel;
4 - protection from LiF; 5 - lead protection;
6 - collimator of gamma quanta;
7 - boron rubber diaphragms;
8 - borated polyethylene collimation assembly;
9 - cadmium-coated polyethylene biological shielding;
10 - neutron beam stop (neutron absorber).

Mass of the samples is about 1 g.

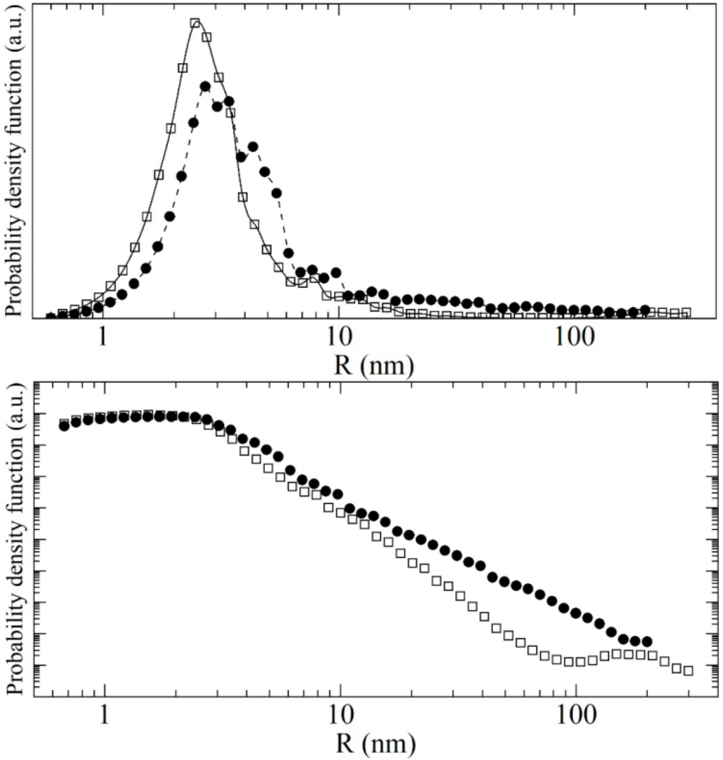
Deagglomeration: nanoparticle cluster breaking

$$P_{REF}^{after}/P_{REF}^{before} \approx 1.10$$
$$\rho_{bulk}^{after}/\rho_{bulk}^{before} \approx 3$$

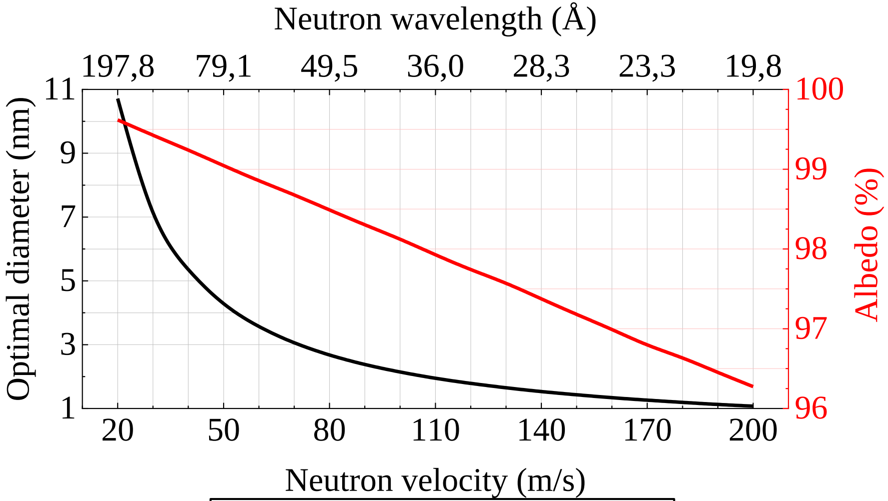


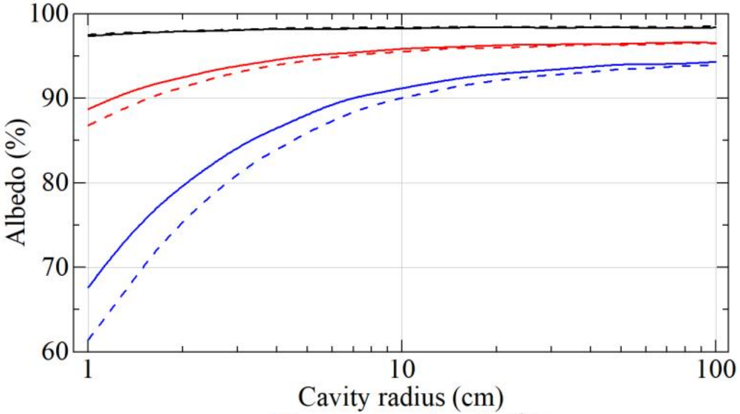
The relative reflectivity of the 3 cm thick F-DND layer (dotted), FD-DND (dashed) and the infinity thick FD-DND layer (solid line).

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

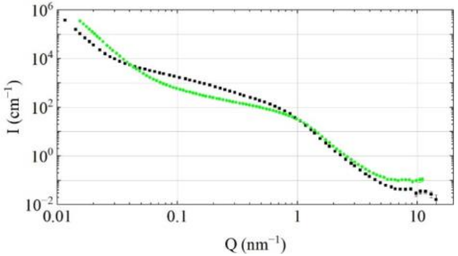


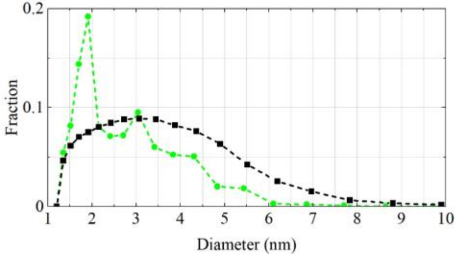
Size separation of nanoparticles

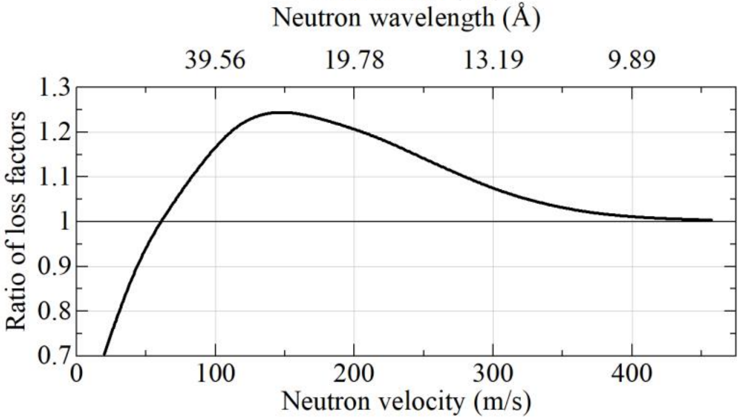




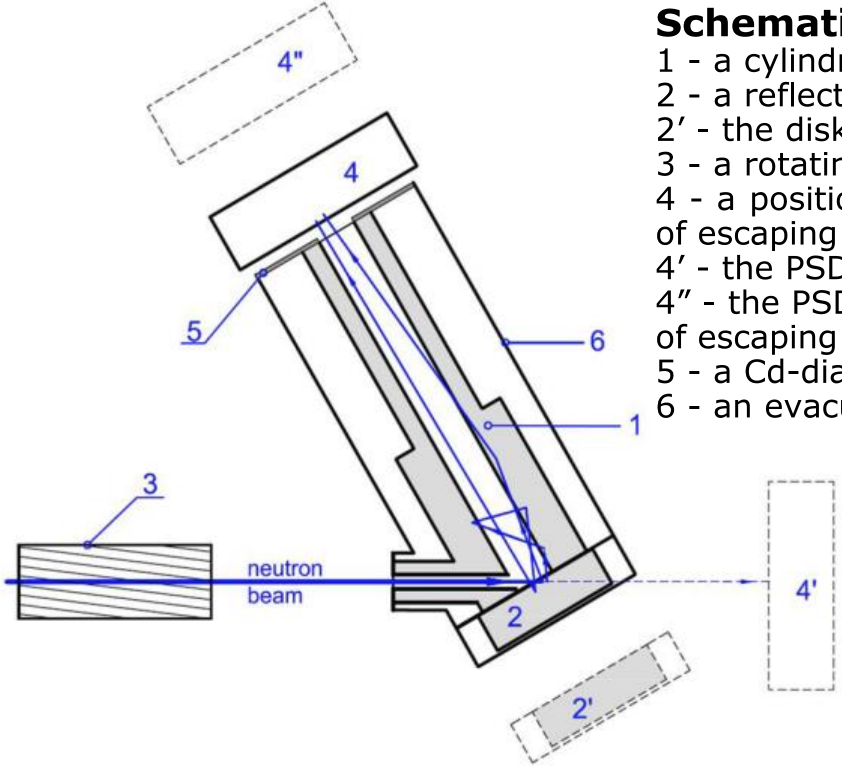
$$\boxed{P_{REF}^{max}:\ R_{opt} \approx 0.27\lambda}$$







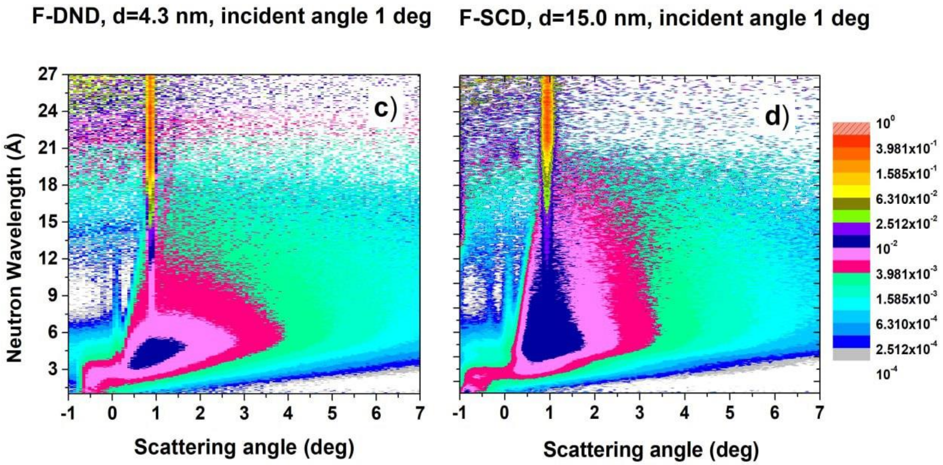
Enhanced directional extraction of VCNs



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.

Quasi-specular reflection of cold neutrons


F-DND, d=4.3 nm, incident angle 1 deg

F-SCD, d=15.0 nm, incident angle 1 deg

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).

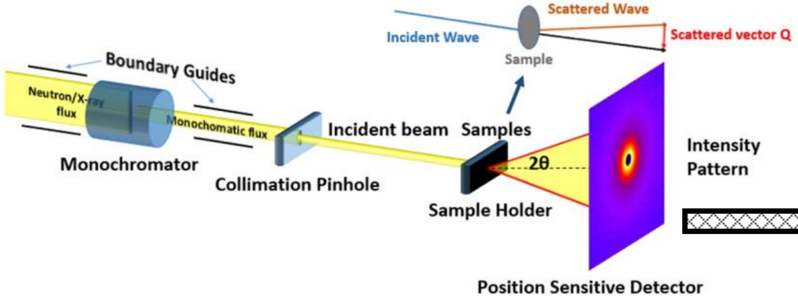
Nanodiamond sizes in the samples: (c) 4.3 nm; (d) 15 nm.

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

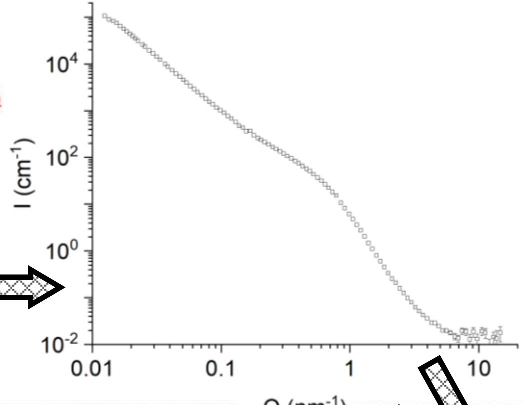
The effect of the size (**d**) of nanoparticles on the probability of quasi-mirror reflection ($\mathbf{P_{Q\text{-}S}}$) of neutrons from the surface of diamond nanopowders, and the width of the angular distribution (**$\Delta\alpha$**) of reflected neutrons:

- **Cold neutrons ($\lambda>4$Å):** with increasing **d**, $\mathbf{P_{Q\text{-}S}}$ increases and **$\Delta\alpha$** decreases
- **Thermal neutrons ($\lambda<4$Å):** with increasing **d**, $\mathbf{P_{Q\text{-}S}}$ decreases due to an increase in Bragg scattering.

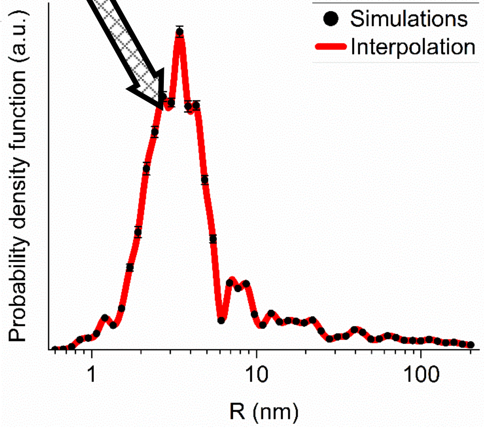
Models of nanopowder structure and neutron transport

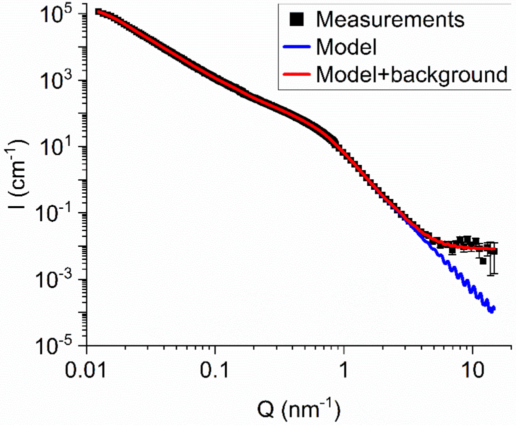


The typical scheme of the SANS experiment.

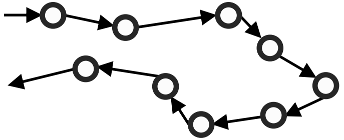


Measured intensity I of scattered neutrons as a function of the transferred momentum Q for the powder of detonation nanodiamonds.





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



Potential practical applications

- Increasing UCN/VCN source intensity at the IBR-2/NEPTUN reactors.
- Looking for neutron-antineutron oscillations: NNBAR@ESS, the ideas of a VCN fountain, etc.
- VCN storage in material traps to achieve the highest densities of low-energy neutrons.
- 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

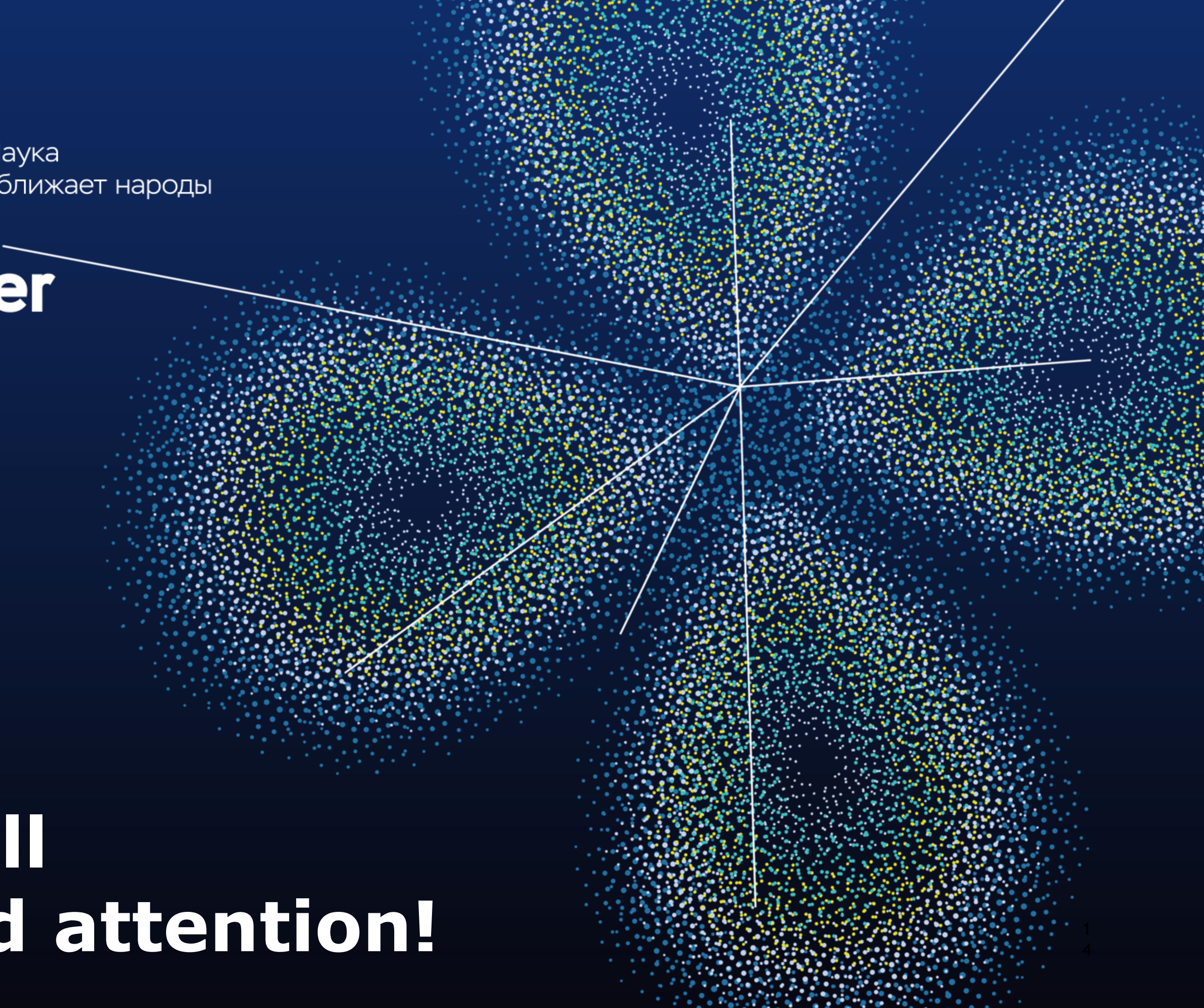
- Optimization of powder density for neutron reflection.
- Study of radiation resistance of fluorinated nanodiamonds.
- Extending the applicability of the transport model to the thermal neutrons by taking into account the crystal structure of nanodiamonds.
- Study of the time dependence of very cold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

Conclusions

- Low-energy neutrons are a very promising spectrum for both applied and fundamental physics applications.
- Nanodiamonds are the most efficient material for VCN reflectors.
- The technologies of nanodiamond purification, fluorination, deagglomeration, and separation is validated and can be used for industrial scaling.
- The VCN reflector shows a gain factor of around 10 times for the VCN directional extraction. It might be even higher for the full-scale reflector in case of a real VCN source.

Наука
сближает народы

Science brings nations together



Thank you all for your kind attention!