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NANO-STRUCTURED REFLECTORS FOR SLOW NEUTRONS

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INTRODUCTION

Neutron reflectors play important role in nuclear industry and in neutron research

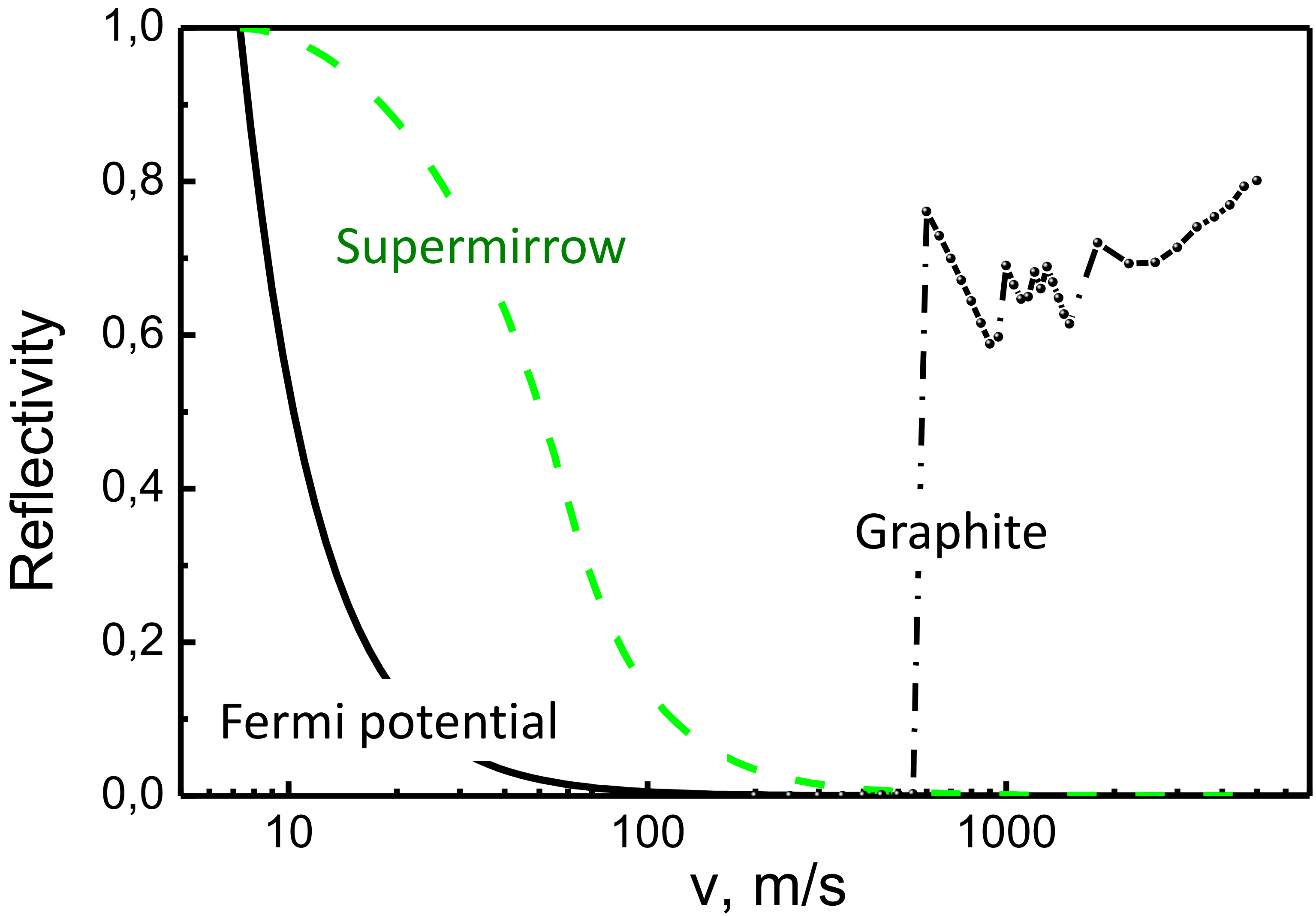
In nuclear reactors the reflectors return neutrons to the active core suchwise it increase a neutron efficiency.

In nuclear research the reflectors used to extract neutrons from a source to an experimental hall with high efficiency, to focus or to turn a neutron beam.

Phenomenon of reflectors is based on elastic neutron scattering.
Well know the two type of reflectors:

- «albedo» reflectors (it mainly used at reactor physics);
- mirrors (it mainly used at neutron optics).

INTRODUCTION



BACKGROUND

UCN → **VCN** → CN

are widely used in precise particle physics experiments

neutrons (v=8÷200 m/c) are very attractive for:

extremely broad applications in various domains: solid state, soft matter, surface physics, magnetism, chemistry, biology, precision studies of the neutron decay and in studies of fundamental symmetries

- **search extra-short-range interactions at neutron scattering;**
- **experiments with neutrons in a whispering gallery;**
- **beam experiment to measure of the neutron decay;**
- **…**
- **spin-echo technique;**
- **reflectometry;**
- **high-resolution inelastic scattering;**
- **small angle scattering;**
- **Diffraction;**
- **…**

BACKGROUND

Advantage of VCN:

- 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;
- possibility structure analysis of large molecular complexes;
- …

Disadvantage of VCN:

Small flux intensity (as for UCN it is only part of spectra)

BACKGROUND

There are a lot of papers concerning the VCN applications and perspectives:

- R.Golub “The production of very cold neutrons” **Physics Letters A** Volume 38, Issue 3, 31 January **1972**, Pages 177-178
- V. V.Golikov, V.I.Lushchikov, and F.L.Shapiro “Production of very cold neutrons” Zh. Eksp. Teor.Fiz.64, 73-81(January **1973**)
- Roland Gähler, Anton Zeilinger “Wave-optical experiments with very cold neutrons” American Journal of Physics **59**, 316 (**1991**)
- E. M. Rasel, K. Eder, J. Felber, R. Gähler, R. Golub, W. Mampe, A. Zeilinger (**1994**) “Interferometry with very Cold Neutrons”. In: van der Merwe A., Garuccio A. (eds) Waves and Particles in Light and Matter. Springer, Boston, MA
- van der Zouw G., Weber M., Felber J., Gahler Roland, Geltenbort P., Zeilinger A. (**2000**). “Aharonov–Bohm and gravity experiments with the very-cold-neutron interferometer.” NIM A: 440. 568-574
- R. Georgii , N. Arend , P. Böni , D. Lamago , S. Mühlbauer & C. Pfleiderer “Scientific Review: MIRA: Very Cold Neutrons for New Methods” **Neutron News** Volume 18, **2007 - Issue 2 ,** Pages 25-28
- V.V. Nesvizhevsky “Reflectors for VCN and applications of VCN” REVISTA MEXICANA DE F´ISICA S **57** (1) 1–5 (**2011**)

BACKGROUND

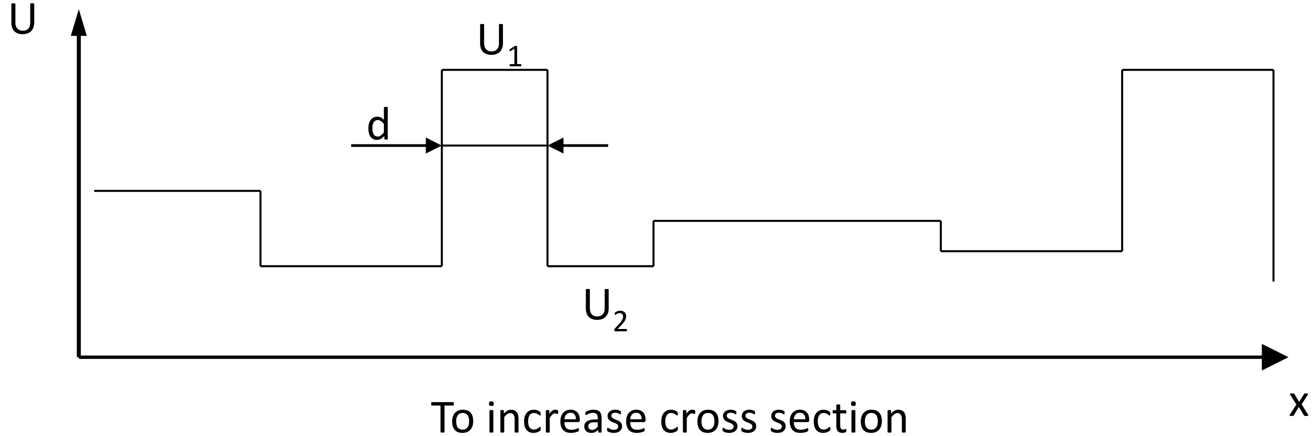
Dedicated workshops:

- **«Workshop on Applications of the Very Cold Neutron Source»** 21-24 August 2005 at IPNS-ANL
- **«Present Status and Future of Very Cold Neutron Applications»** 13-14 February 2006 Paul Scherrer Institute - Switzerland
- **«Very Cold Neutron Source for the Second Target Station Workshop»** 27-28 April 2016 Oak Ridge National Laboratory, SNS Building 8600

BACKGROUND

Basic physics:

Scattering of neutrons on inhomogeneous



To increase cross section

$$\sigma_s \sim (U_1 - U_2)^2 \cdot \begin{cases} d^6 & \lambda >> d \\ d^2 & \lambda << d \end{cases}$$

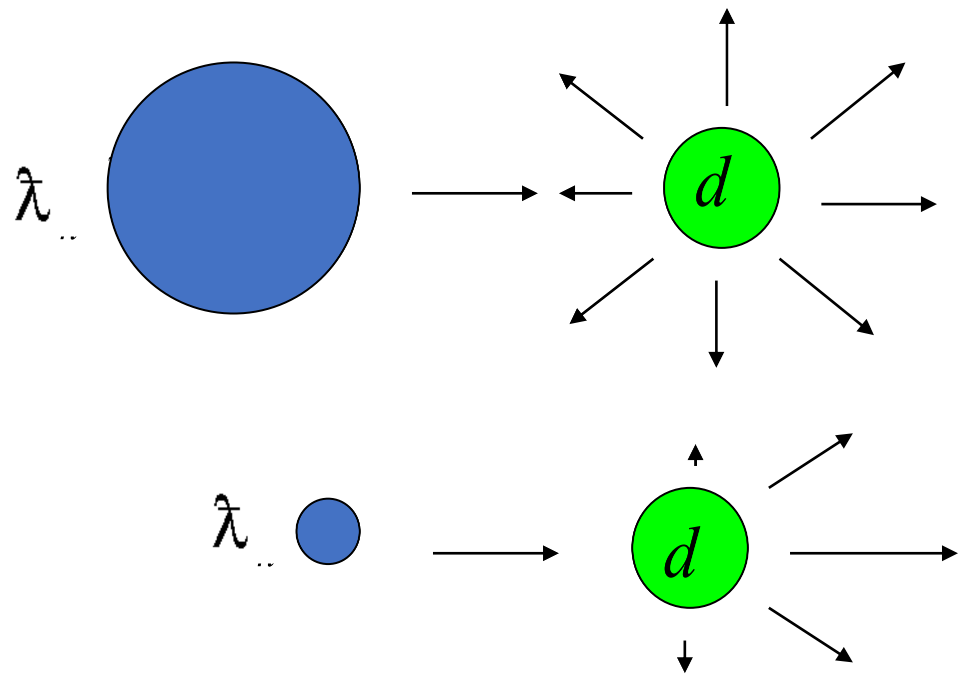
it is good to have big contrast and big particles

BACKGROUND

Basic physics:

Scattering of neutrons on inhomogeneous

But for big particles forward scattering is dominate



So we have diffusion motion of a neutrons in a medium and the best choice is:

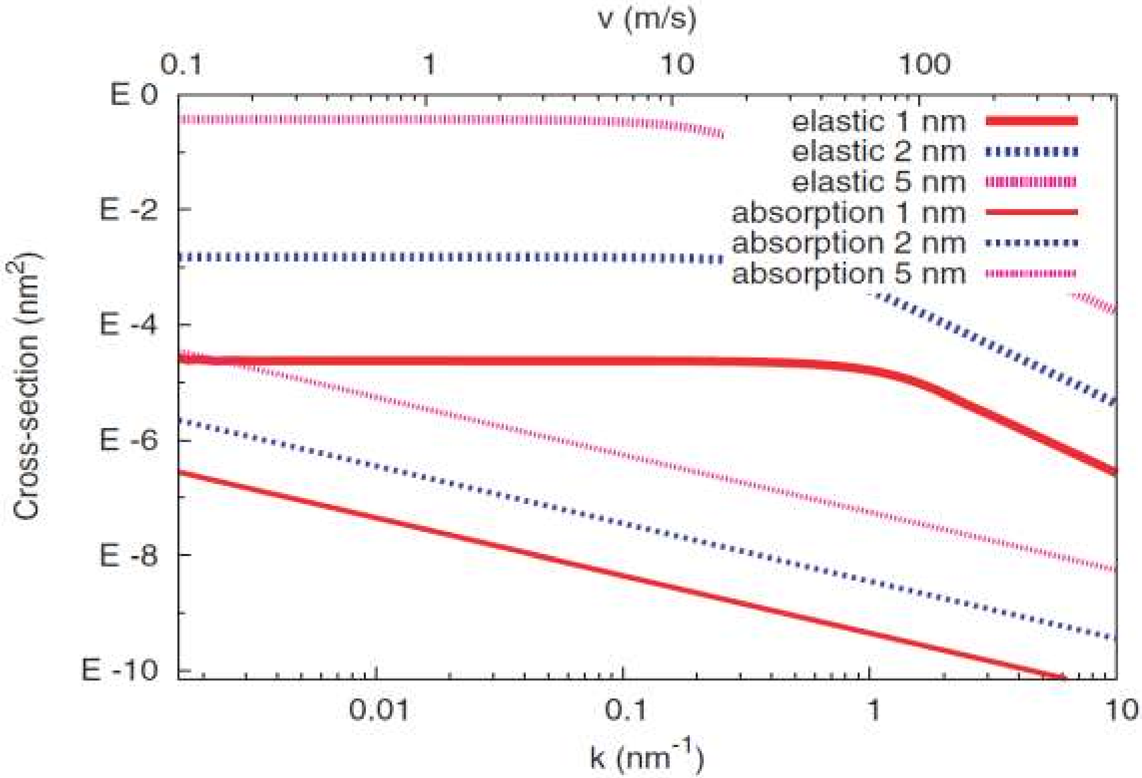
-have σ_a and σ_{in} as small as possible;

-have dimensions of inhomogeneous $d \sim \lambda_n$

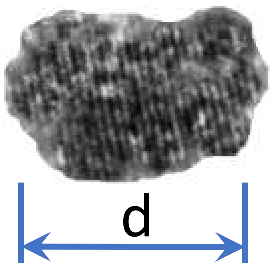
BACKGROUND

Basic physics:

Scattering of neutrons on inhomogeneous



Coherent interaction with d size particle like unit



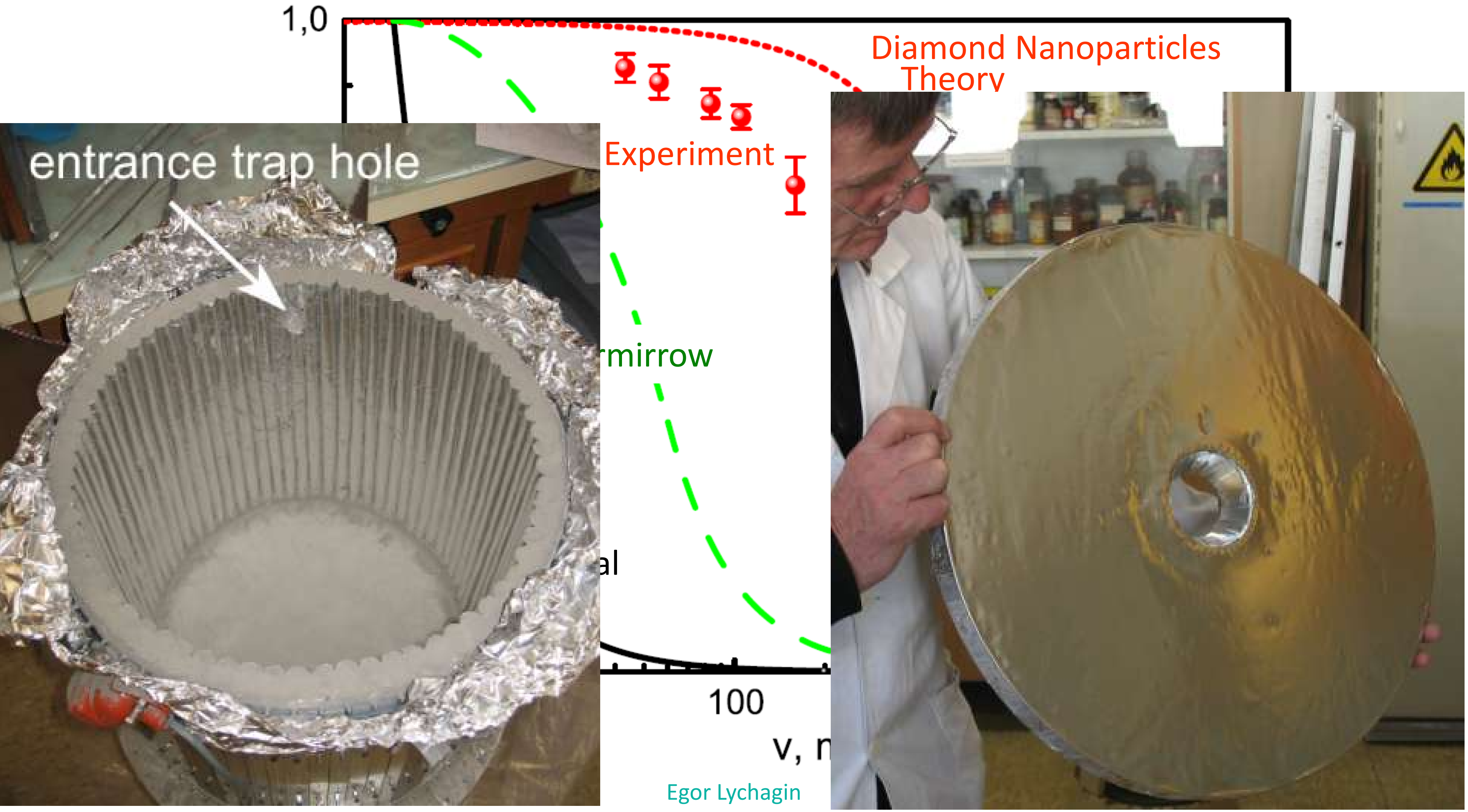
Interaction probability $\sim d^6$

Optimal situation (large interaction probability, large scattering angle):

$$\lambdabar \sim d \qquad v = 100\, m/s \rightarrow \lambdabar$$

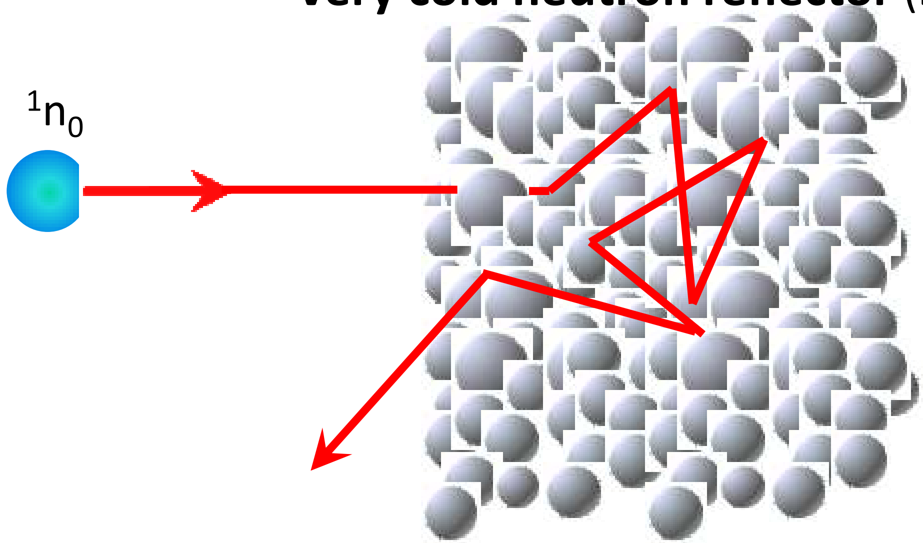
BACKGROUND

Measurement of VCN storage in diamond nanopowder trap:



BACKGROUND

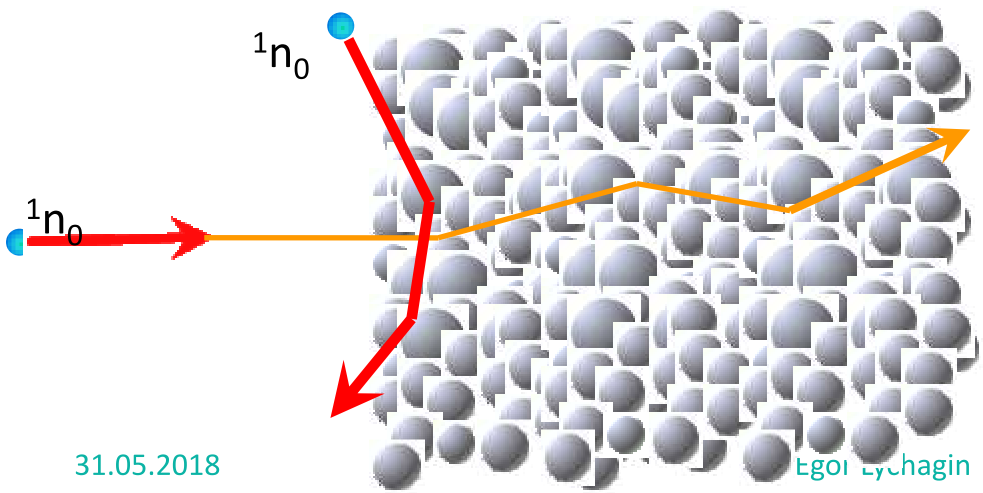
Very cold neutron reflector ($E<10^{-4}$ eV)



- Large scattering probability
- Large scattering angle
- Small penetration

Possible to have effective reflector at any incidence angle

Cold neutron reflector ($E<5\cdot10^{-3}$ eV)



- Small scattering probability
- Small scattering angle
- Deep penetration

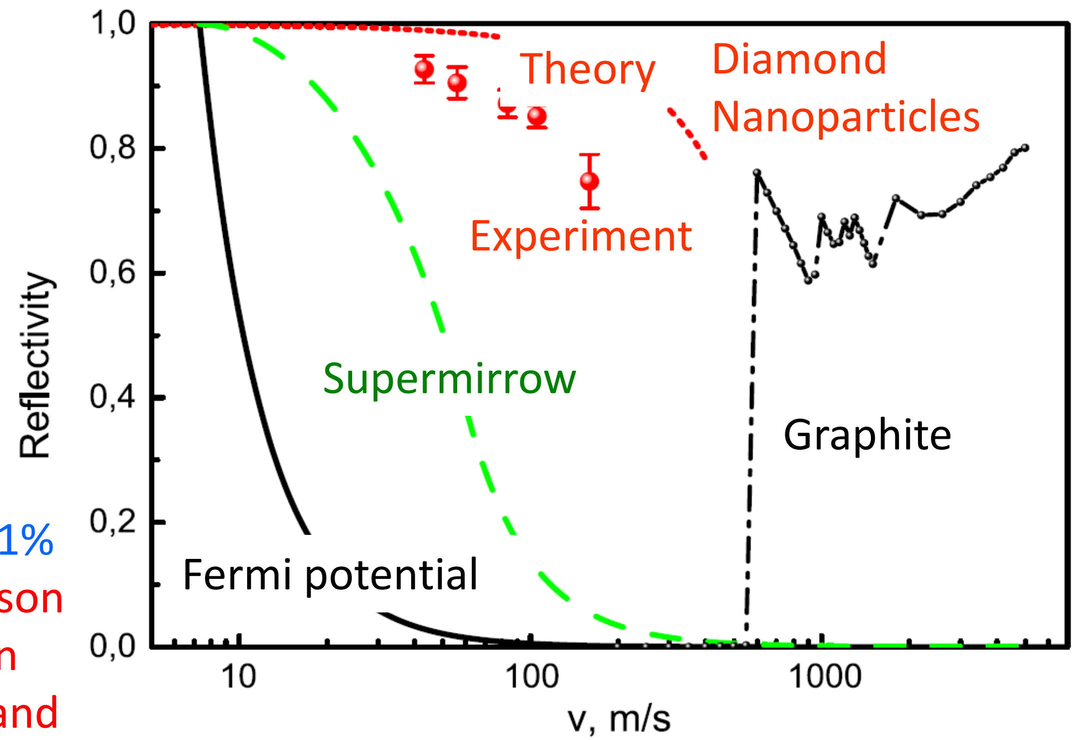
Possible to have effective reflector only at small incidence angle

BACKGROUND

Diamonds of detonation synthesis (Nanodiamond) is the best choice

Advantages: big "contrast", small size of particles, small neutron capture

Disadvantages: hydrogen admixture: ~1% of nuclei. It is main reason of discrepancy between theoretical prediction and the experimental result.



Non degased sample $C_{7.4\pm0.15}H$

Degased sample $C_{12.4\pm0.2}H$

Situation at 2010: it is need find a way to clear particles from hydrogen

BACKGROUND

Developing of new technology: reflectors for very cold neutrons

- V.V. Nesvizhevsky, E.V.Lychagin, A.Yu.Musychka, A.V.Strelkov, G. Pignol, K.V. Protasov "The reflection of very cold neutrons from diamond powder nanoparticles" // NIM A **595**, (2008) 631-636
- Lychagin E.V., Muzychka A.Yu., Nekhaev G.V., Nesvizhevsky V.V., Pignol G., Protasov K.V., Strelkov A.V. "Storage of very cold neutrons in a trap with nano-structured walls" Physics Letters B 679 (2009) 186–190
- R. Cubitt, E.V. Lychagin, A.Yu. Muzychka, G.V. Nekhaev, V.V. Nesvizhevsky, G. Pignol, K.V. Protasov, and A.V. Strelkov (2010). "Quasi-specular reflection of cold neutrons from nano-dispersed media at above-critical angles." NIM A 622: 182-185.
- A. R. Krylov, E. V. Lychagin, A. Yu. Muzychka, V. V. Nesvizhevsky, G. V. Nekhaev, A. V. Strelkov, and A. S. Ivanov "Study of Bound Hydrogen in Powders of Diamond Nanoparticles" // Crystallography Reports, 2011, Vol. 56, No. 7, pp. 102–107

RECENT IMPORTANT RESULTS

Fluorination is a way to clear particles from hydrogen

Non degased sample $C_{7.4\pm0.15}H$

Degased sample $C_{12.4\pm0.2}H$

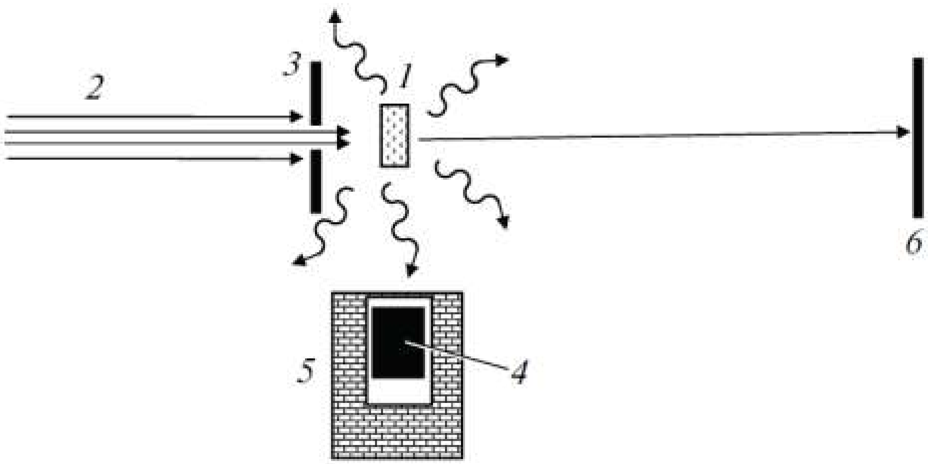


Fig. 1. A scheme of the measurement of a fraction of hydrogen in powder. 1—sample; 2—neutron beam; 3—collimator; 4—γ-detector; 5—detector shielding; 6—neutron detector.

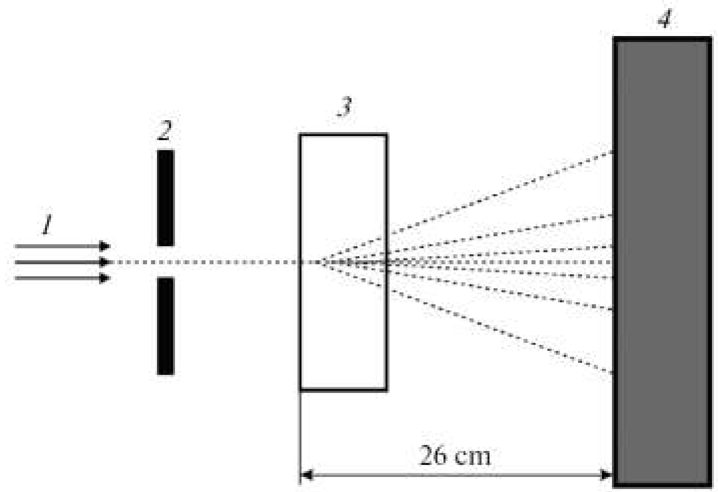


Fig. 3. A scheme of the measurement of the total cross-section of neutron scattering. 1—neutron beam; 2—diaphragm; 3—sample; 4—position-sensitive neutron detector.

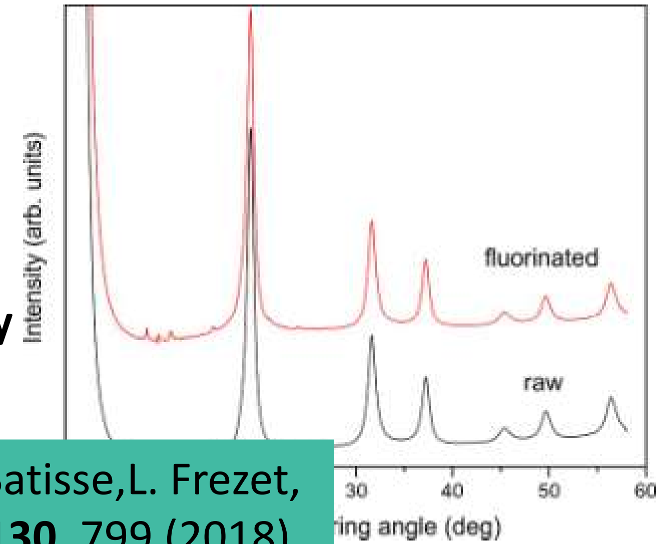
Fluorinated sample $C_{430\pm3}$

RECENT IMPORTANT RESULTS

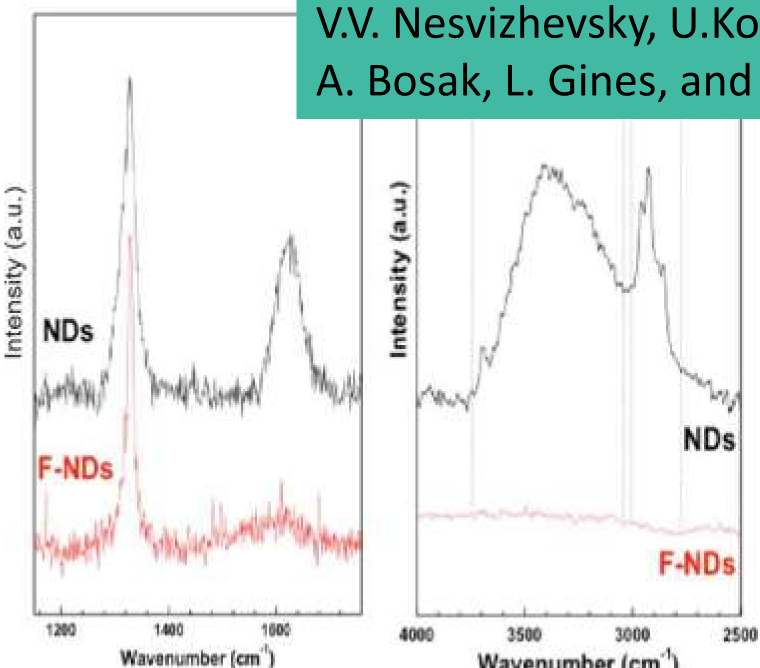
X-ray diffraction patterns of raw and fluorinated nano-diamond powder:

- -Diamond sp^3 cores remain unaffected;
- -Destruction of sp^2 carbon shells.

Destruction of sp^2 carbon will lead to significantly higher efficiency of neutron scattering



V.V. Nesvizhevsky, U.Koester, M. Dubois, N. Batisse,L. Frezet, A. Bosak, L. Gines, and O. Williams, Carbon **130**, 799 (2018).

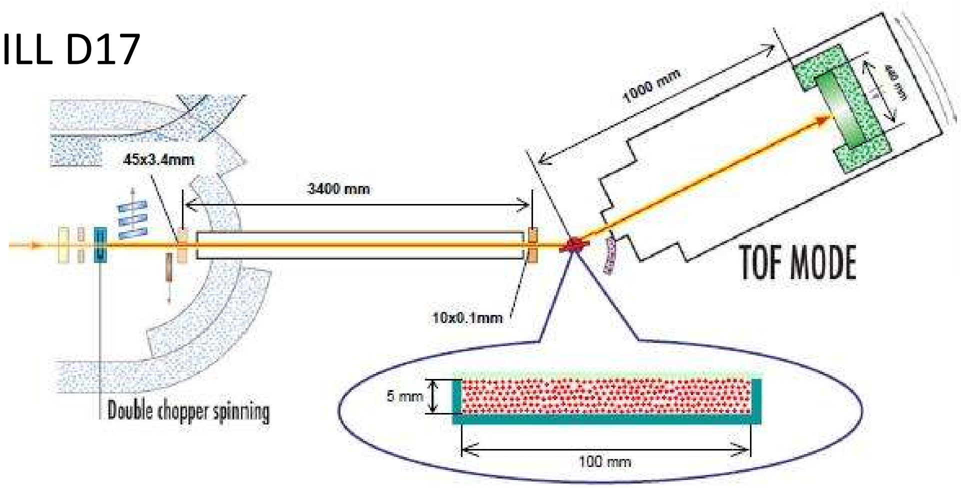


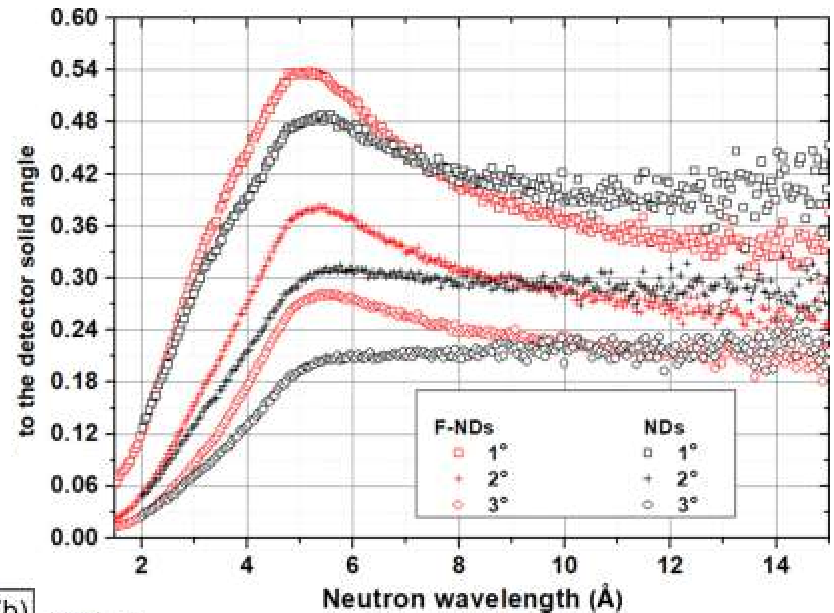
(a) - Raman spectra (inelastic scattering of monochromatic light) of raw and fluorinated nano-diamond;
(b) – FTIR (Fourier-transform infrared spectroscopy) spectra of raw and fluorinated nano-diamond.

Disappearance of sp^2 carbon, C-H and O-H.

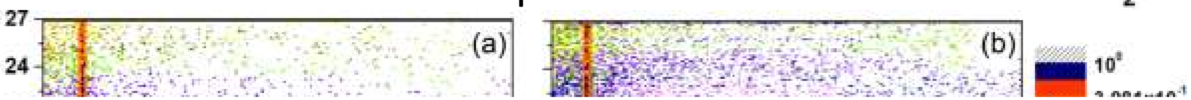
RECENT IMPORTANT RESULTS

ILL D17





Detector's pattern

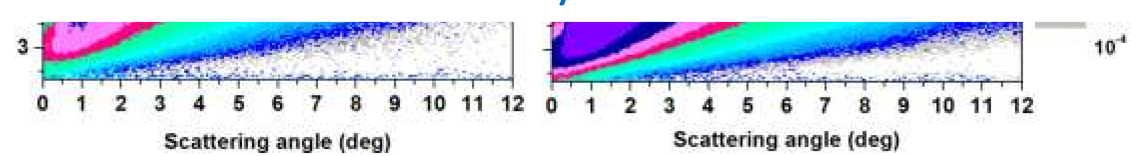


The total probability of

It was reported at ISINN-25 by K.Zhernenkov and published

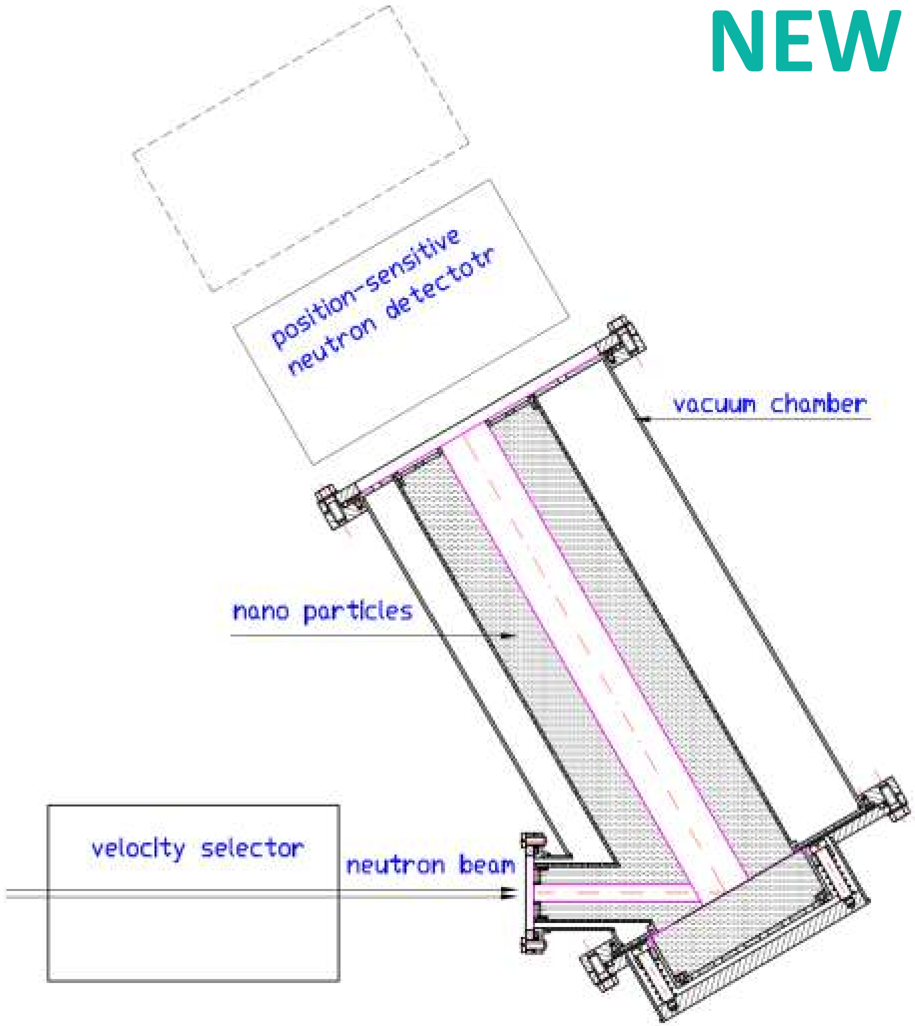
V.V. Nesvizhevsky, M. Dubois, Ph. Gutfreund, E.V. Lychagin, A.Yu. Nezvanov, and K.N. Zhernenkov

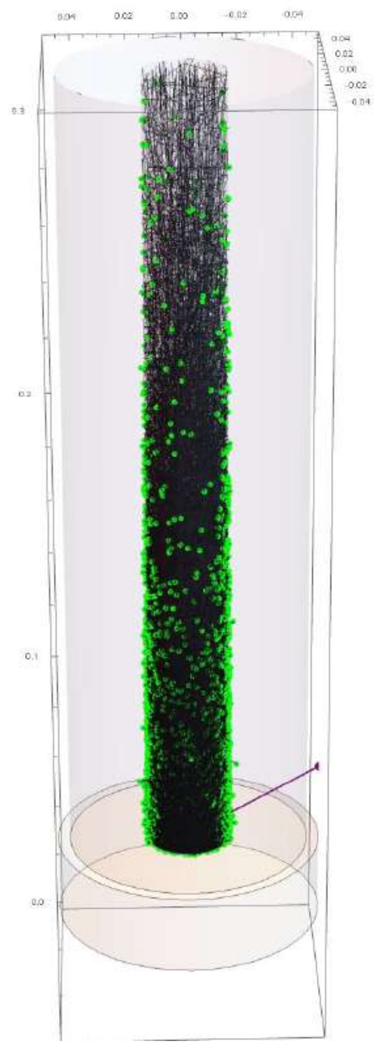
Physical Review A **97** 023629 (2018)

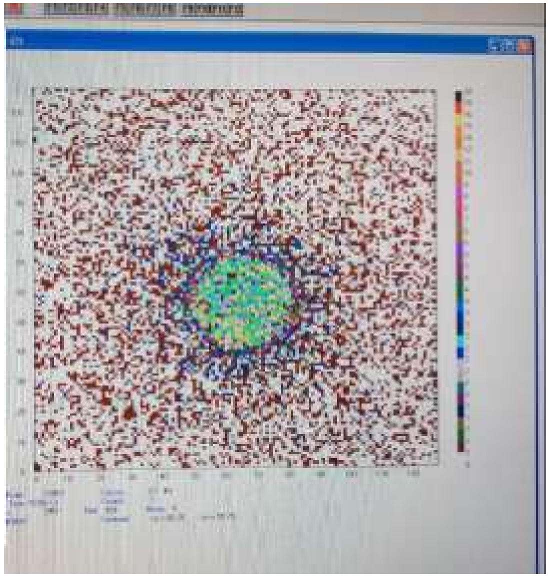


wavelength, for the incidence angles of 1deg., 2deg., 3deg.

NEW RESULT

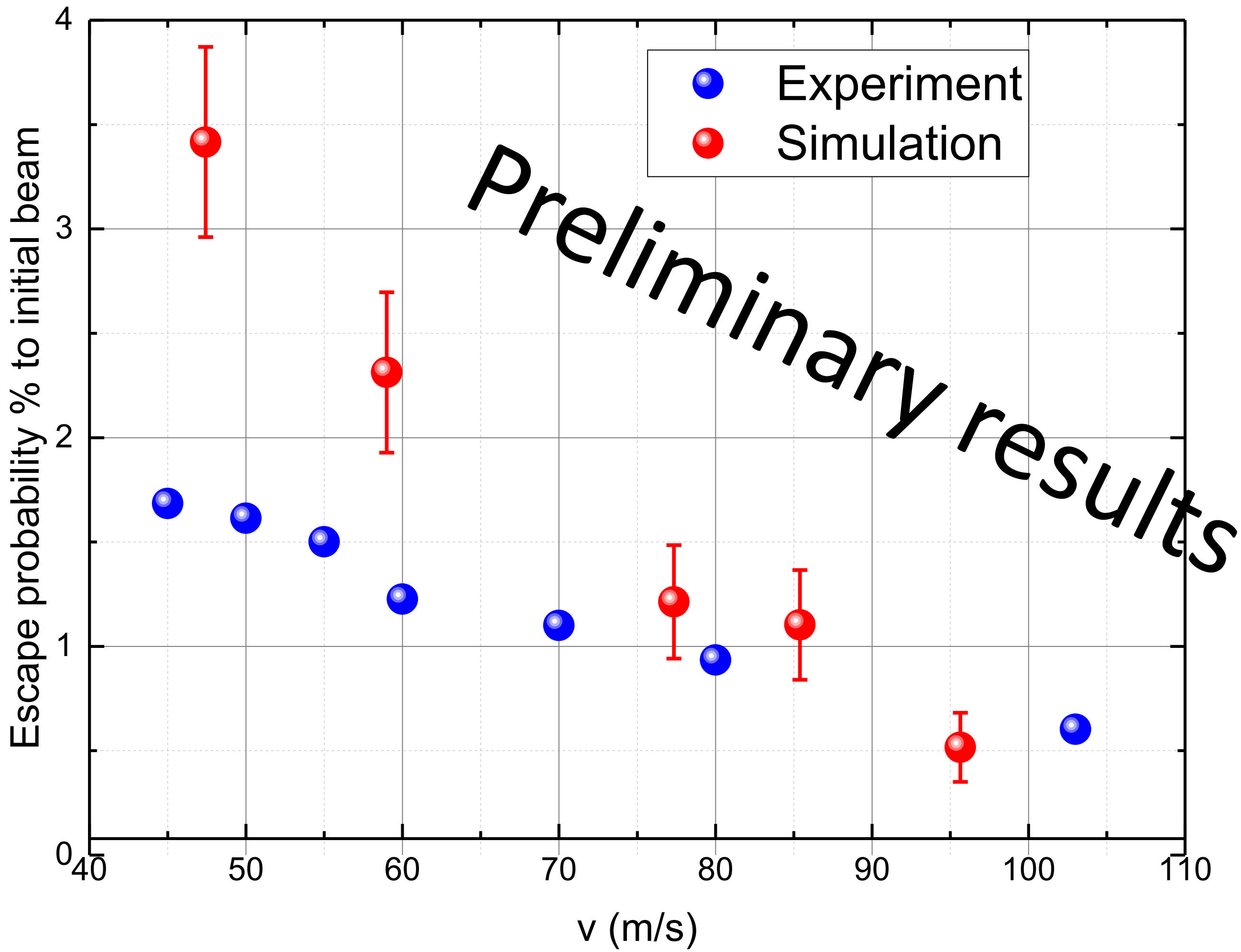




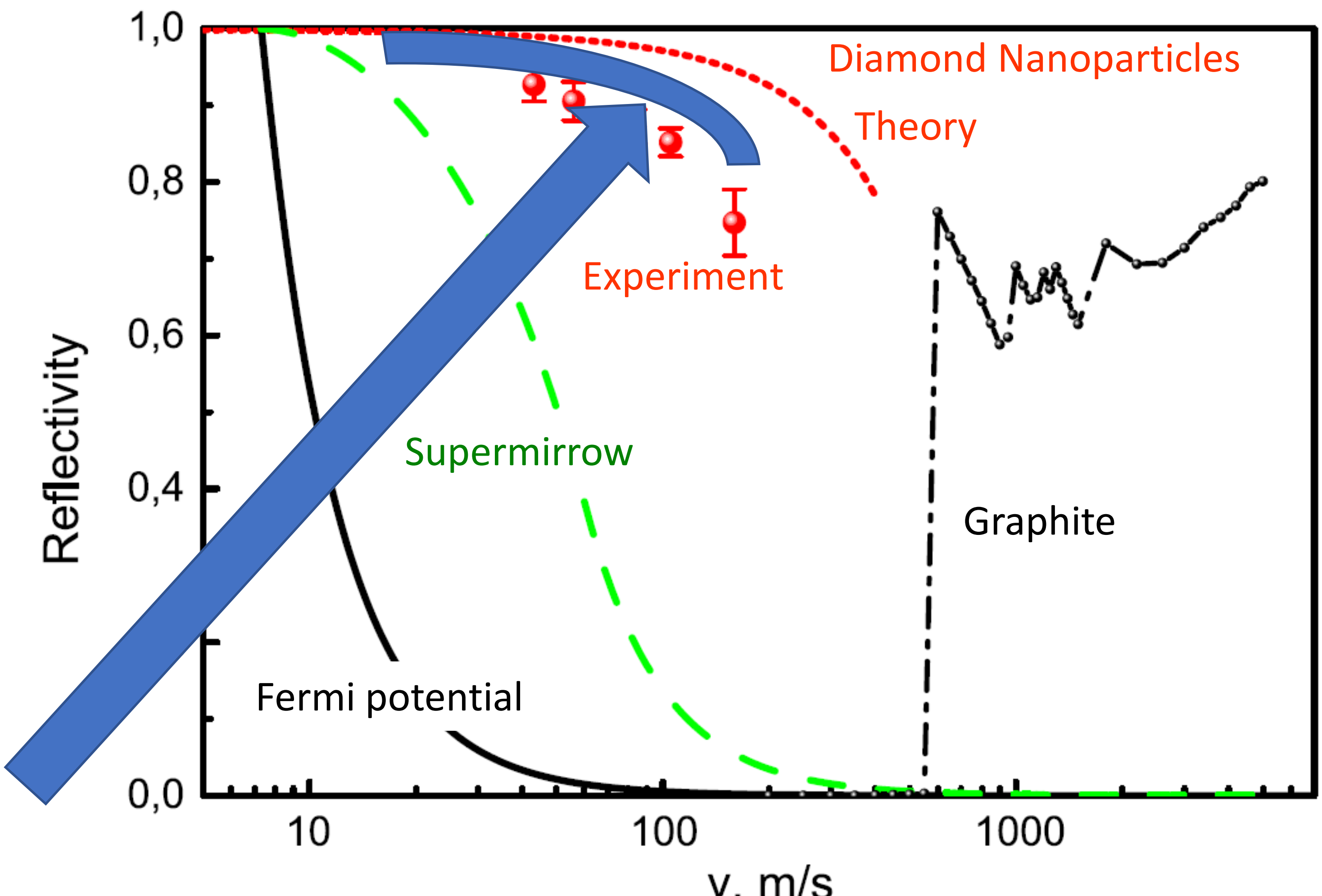


Extracted to the exit hole flux was increased up to 10 times related to flux without the tube (preliminary results)

NEW RESULTS


Escape probability % to initial beam
v (m/s)
0
1
2
3
4
40
50
60
70
80
90
100
110
Experiment
Simulation
Preliminary results

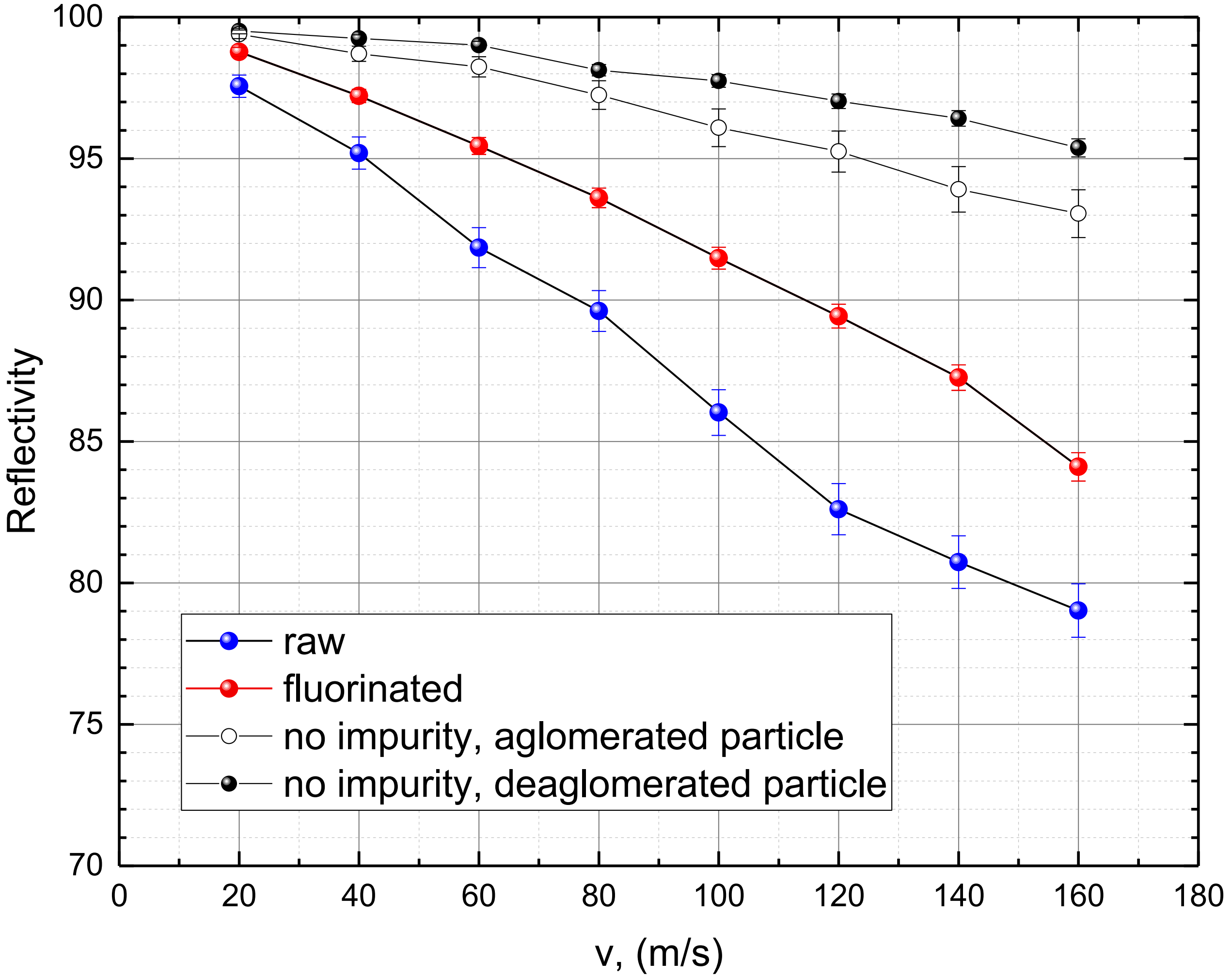
NEW RESULTS



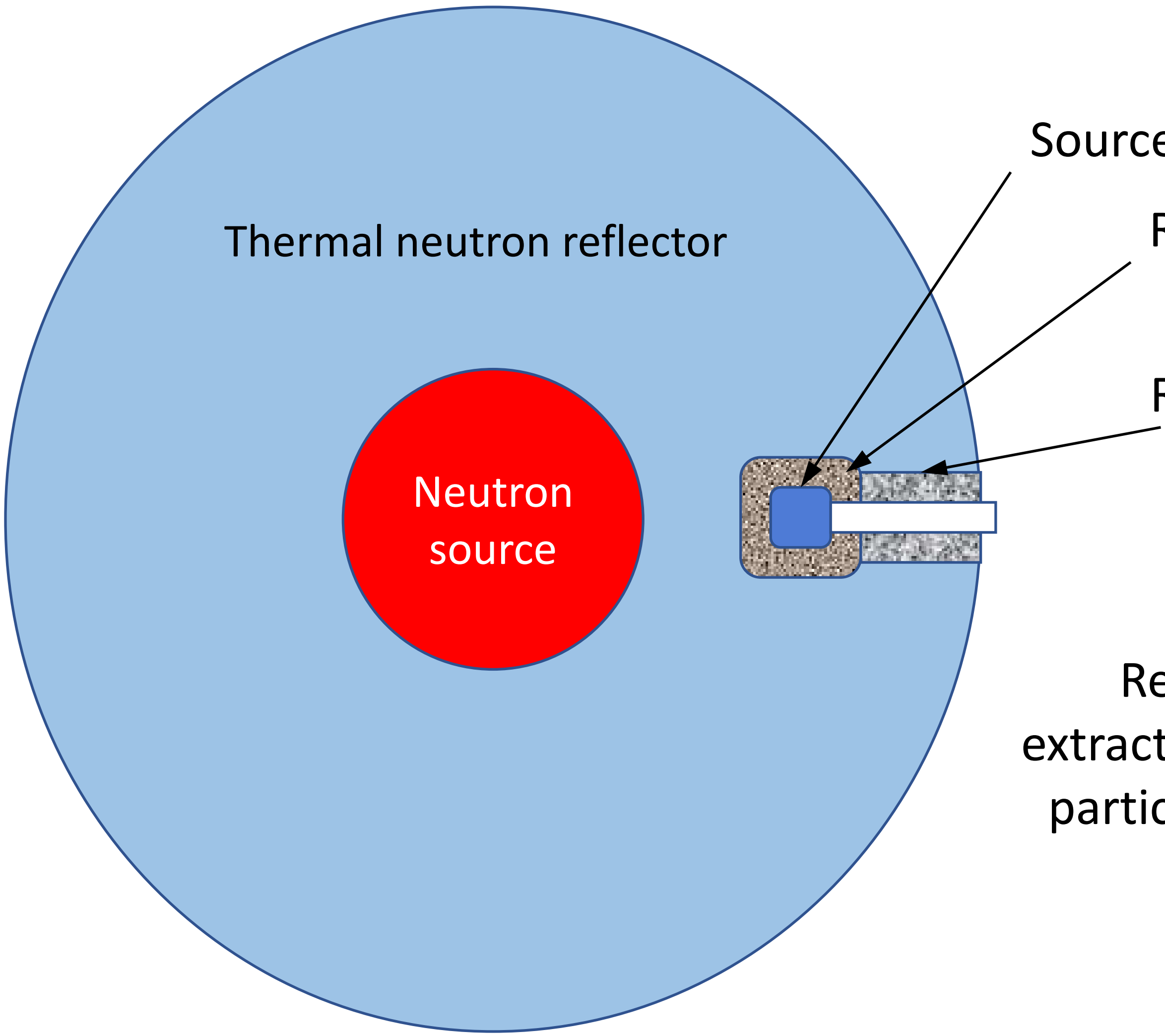
Estimation for fluorinated powder from simulation

NEW RESULTS

Simulation of reflectivity from powder with infinite thickness



NEW RESULTS



Reflector for effective extraction probably should has particles with optimized size distribution

CONCLUSIONS

1. Diamond powder could be used as efficient reflectors for VCN and CN (at glancing angles).
2. Decreasing of hydrogen contamination improved the reflectivity of powder.
3. The extraction of VCN by the reflector was illustrated. The extracted flux of VCN was increased about 10 times.
4. Next steps should be: cleaning the powder from metallic impurity, deagglomeration of particles in the powder.

Thank you for your attention.