Diamond nano-powders: a new type of neutron reflectors. Will it lead to a new generation of slow-neutron sources ?

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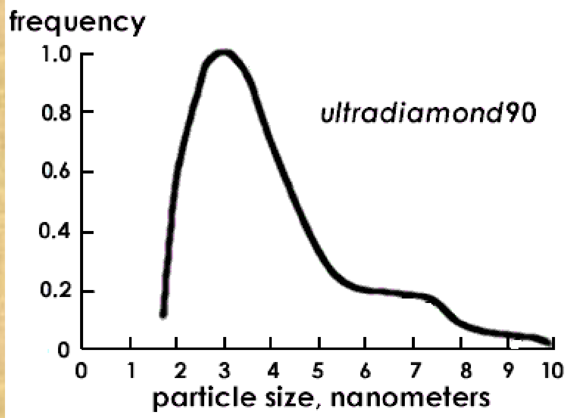
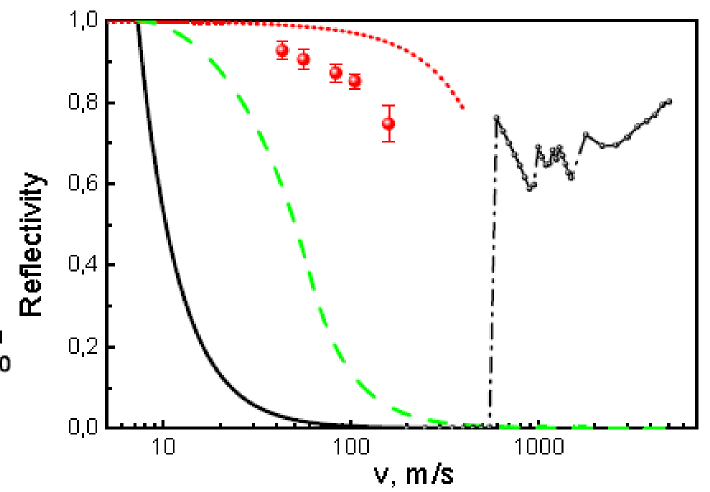
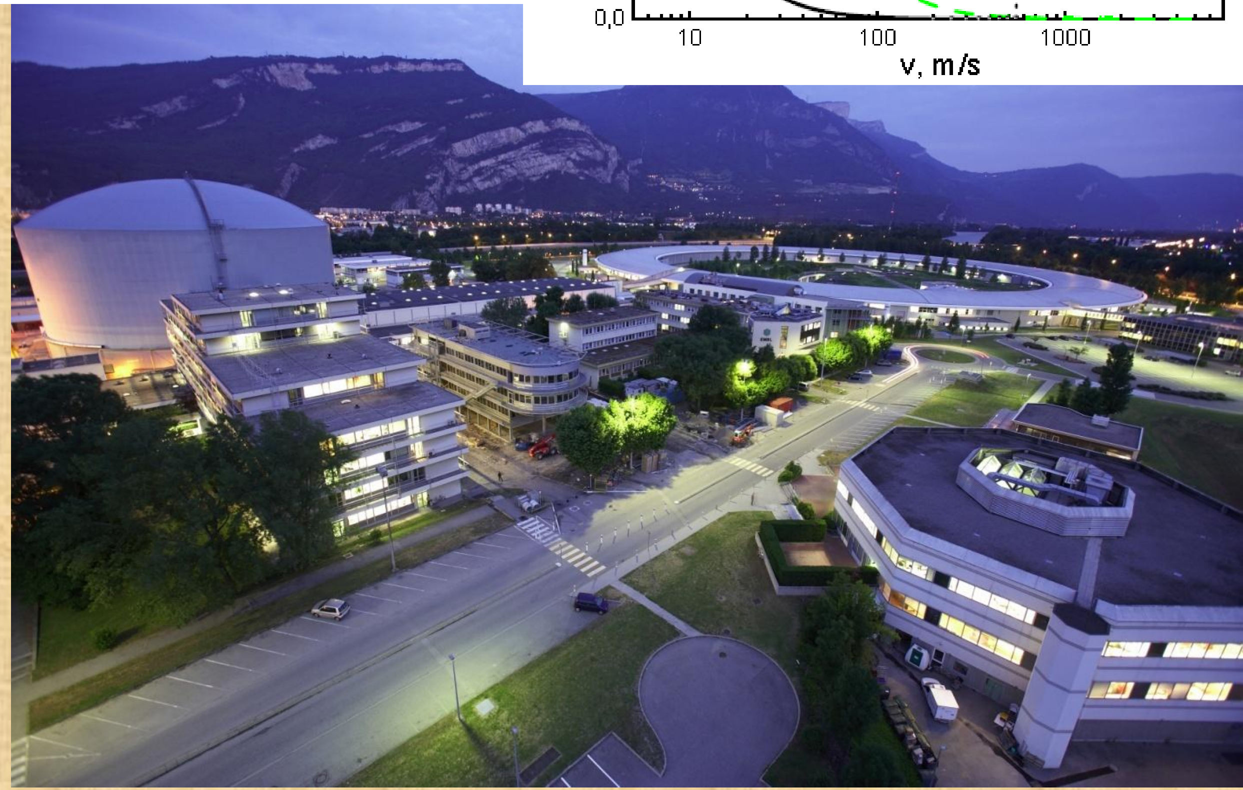
Diamond nano-powders: a new type of neutron reflectors. Will it lead to a new generation of slow-neutron sources ?

1. *Neutron* scattering on *nanoparticles.*
2. *Reflection* of very cold neutrons (VCN) from powders of nanoparticles.
3. *Storage* of VCN in traps.
4. *Quasi-specular* reflection of cold neutrons (CN) from powders.
5. Possible *applications* .
6. Behavior of nanoparticles in high *radiation* fluxes.
7. Conclusions/ Further *developments.*







Introduction

- Neutron-Atom: The neutron-electron interaction is a minor correction compared to the *neutron-nuclei* interaction (except for the case of strongly magnetized materials)

- Neutron-Nucleus: As the wavelength of a slow neutron is larger than the size of a nucleus, we always deal with isotropic *s-scattering* and can characterize it with a single parameter: a scattering length

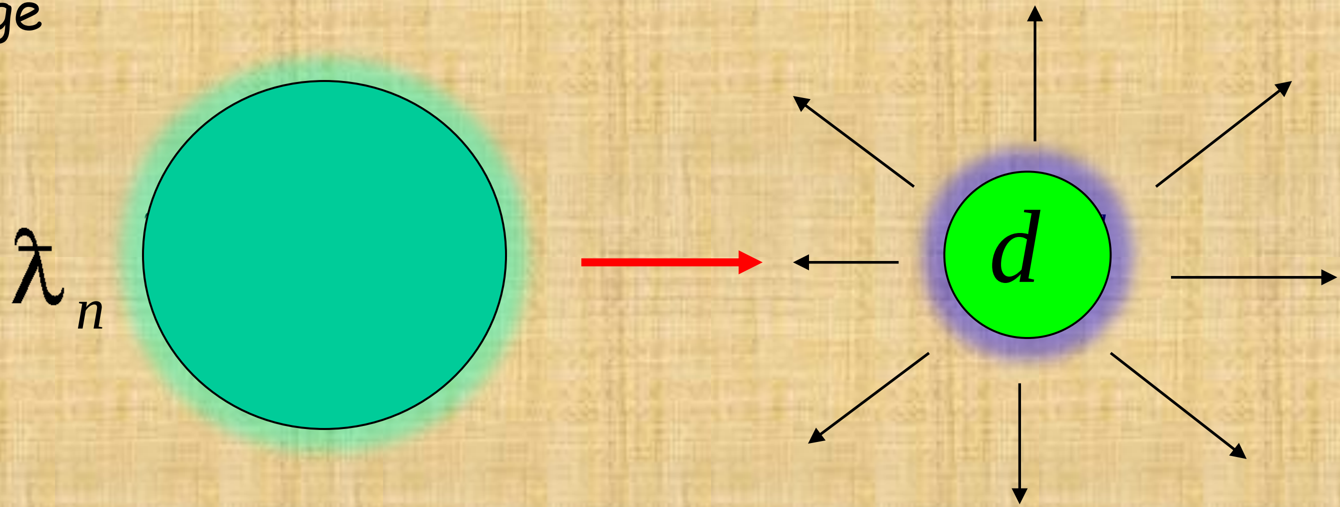
- Neutron-Matter: As the wavelength of a slow neutron is also larger than a typical inter-atomic distance, we deal with *coherent scattering* of neutrons at many nuclei simultaneously

- Optical Potential: As a result, any medium can be represented as a uniform effective *optical potential*

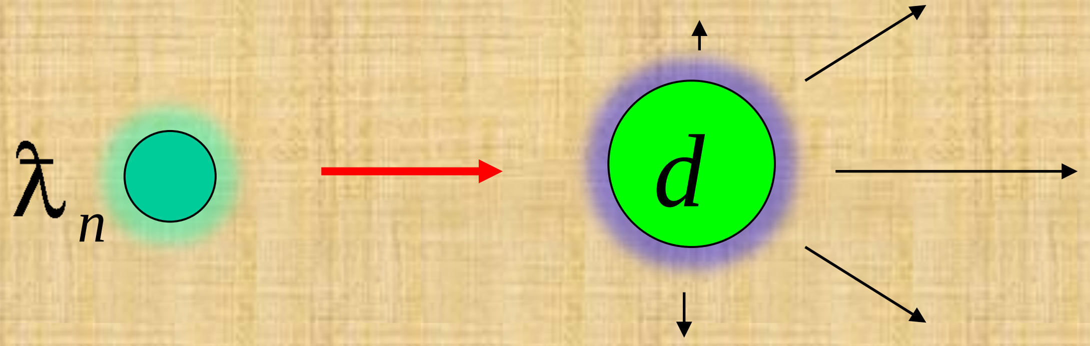
- Potential Strength: A typical value of the optical neutron-nuclei potential is 10^{-7} *eV* (could be though of as a typical nuclear potential of 10 MeV diluted over volume)

Neutron scattering on nanoparticles

Two contradicting conditions:
1) Cross-section increases rapidly as a function of the nanoparticle size, if the size is small; 2) Angular divergence and cross-section drop down rapidly, if the size is large



The "optimum" neutron wavelength is approximately equal to the nanoparticle size



Neutron scattering on nanoparticles

Provided this "optimum" condition is met, the cross-section of coherent elastic scattering of a neutron on a nanoparticle is that large that it could be measured in square nanometers !

What is the best choice of the nanoparticle material and size ?

The "optimum" neutron wavelength is approximately equal to the nanoparticle size

Neutron scattering on nanoparticles

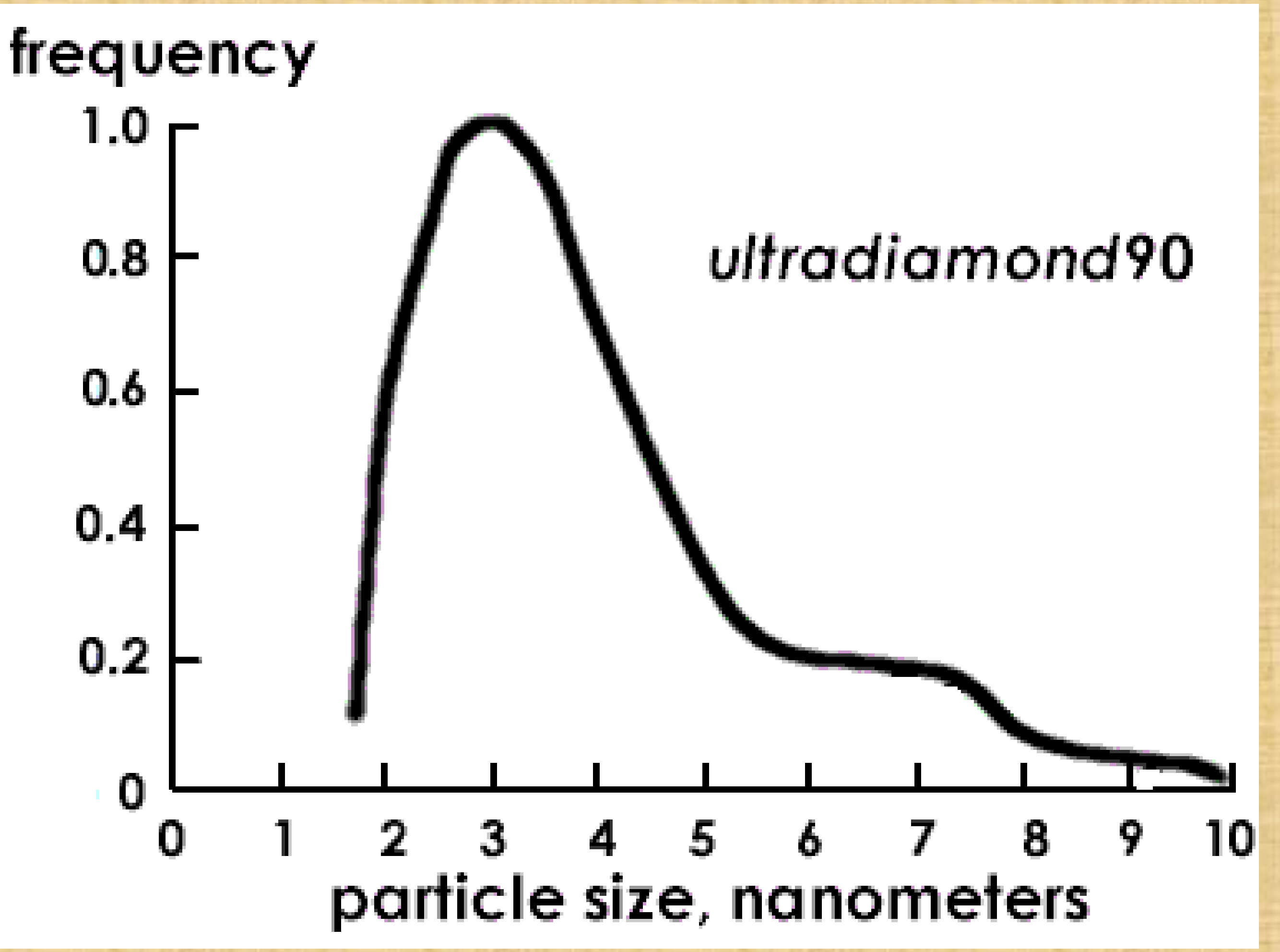
Neutron scattering lengths and cross sections

Isotope	conc	Coh b	Inc b	Coh xs	Inc xs	Scatt xs	Abs xs
...							
B	---	5.30-0.213*i*	---	3.54	1.7	5.24	767.(8.)
10B	20	-0.1-1.066*i*	-4.7+1.231*i*	0.144	3	3.1	3835.(9.)
11B	80	6.65	-1.3	5.56	0.21	5.77	0.0055
C	---	6.6460	---	5.551	0.001	5.551	0.0035
12C	98.9	6.6511	0	5.559	0	5.559	0.00353
13C	1.1	6.19	-0.52	4.81	0.034	4.84	0.00137
N	---	9.36	---	11.01	0.5	11.51	1.9
14N	99.63	9.37	2.0	11.03	0.5	11.53	1.91
15N	0.37	6.44	-0.02	5.21	0.00005	5.21	0.000024
...							

NIST
National Institute of Standards and Technology
U.S. Department of Commerce

Neutron scattering on nanoparticles

Diamond nanoparticles produced by means of explosion in a closed volume is an evident candidate



Neutron scattering on nanoparticles

We neglected the relatively complex internal structure of the nanoparticle, choosing to modulate it as a uniform sphere. The neutron–nanoparticle elementary interaction was calculated using the first Born approximation. The amplitude for a neutron with energy $\hbar^2/2mk^2$ to be scattered at a spherical nanoparticle with radius R and Fermi potential V, at an angle θ is equal to

$$f(\theta) = -\frac{2m}{\hbar^2} VR^3 \left(\frac{\sin(qR)}{(qR)^3} - \frac{\cos(qR)}{(qR)^2} \right) \quad (1)$$

where $q = 2k\sin(\theta)$ is the transferred momentum. The total elastic cross-section is therefore equal to

$$\sigma_s = \int |f|^2 \, d\Omega = 2\pi \left| \frac{2m}{\hbar^2} V \right|^2 R^6 \frac{1}{(kR)^2} I(kR) \quad (2)$$

where

$$I(kR) = \frac{1}{4} \left(1 - \frac{1}{(2kR)^2} + \frac{\sin(4kR)}{(2kR)^3} - \frac{\sin^2(2kR)}{(2kR)^4} \right). \quad (3)$$

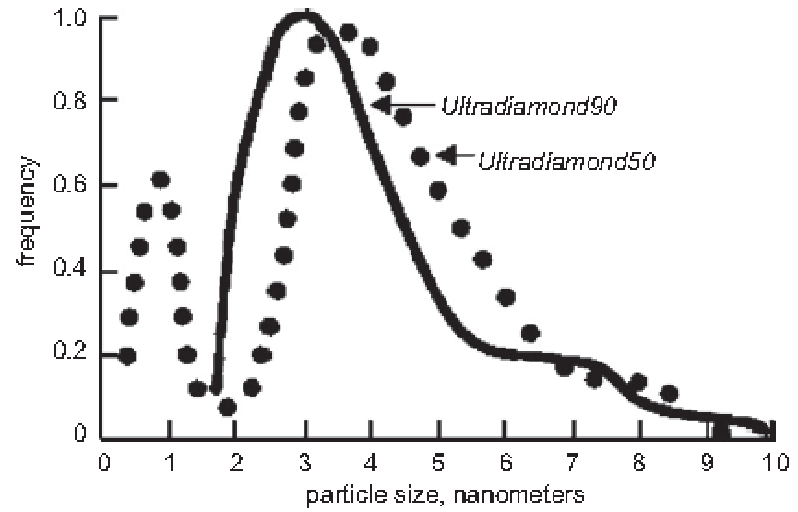


Fig. 4. The size distribution of the diamond nanoparticles in the powder "ultradiamond90".

Neutron scattering on nanoparticles

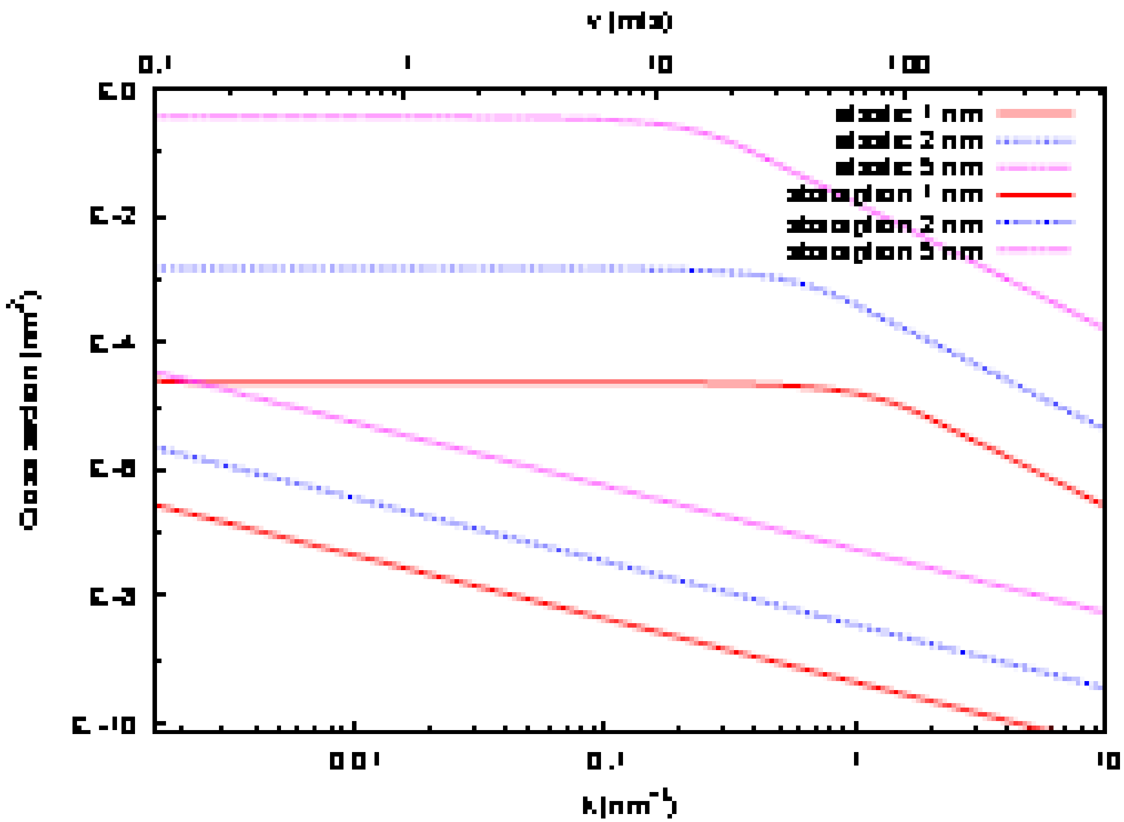


FIG. 1: Elastic and absorption cross sections as a function of neutron velocity, for three values of the deuterium nanoparticles' radii: 1, 2, and 5 nm.

Neutron scattering on nanoparticles

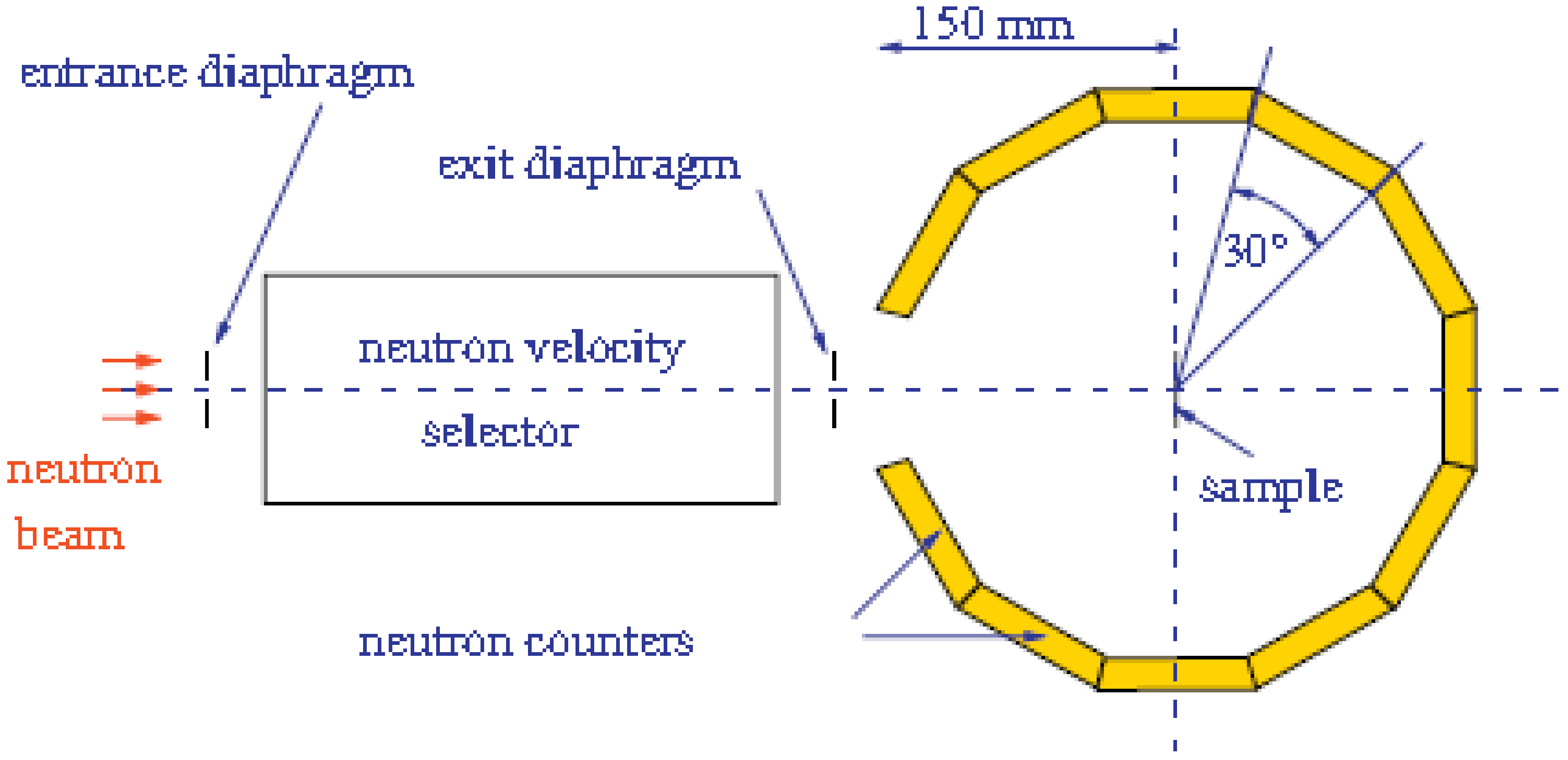
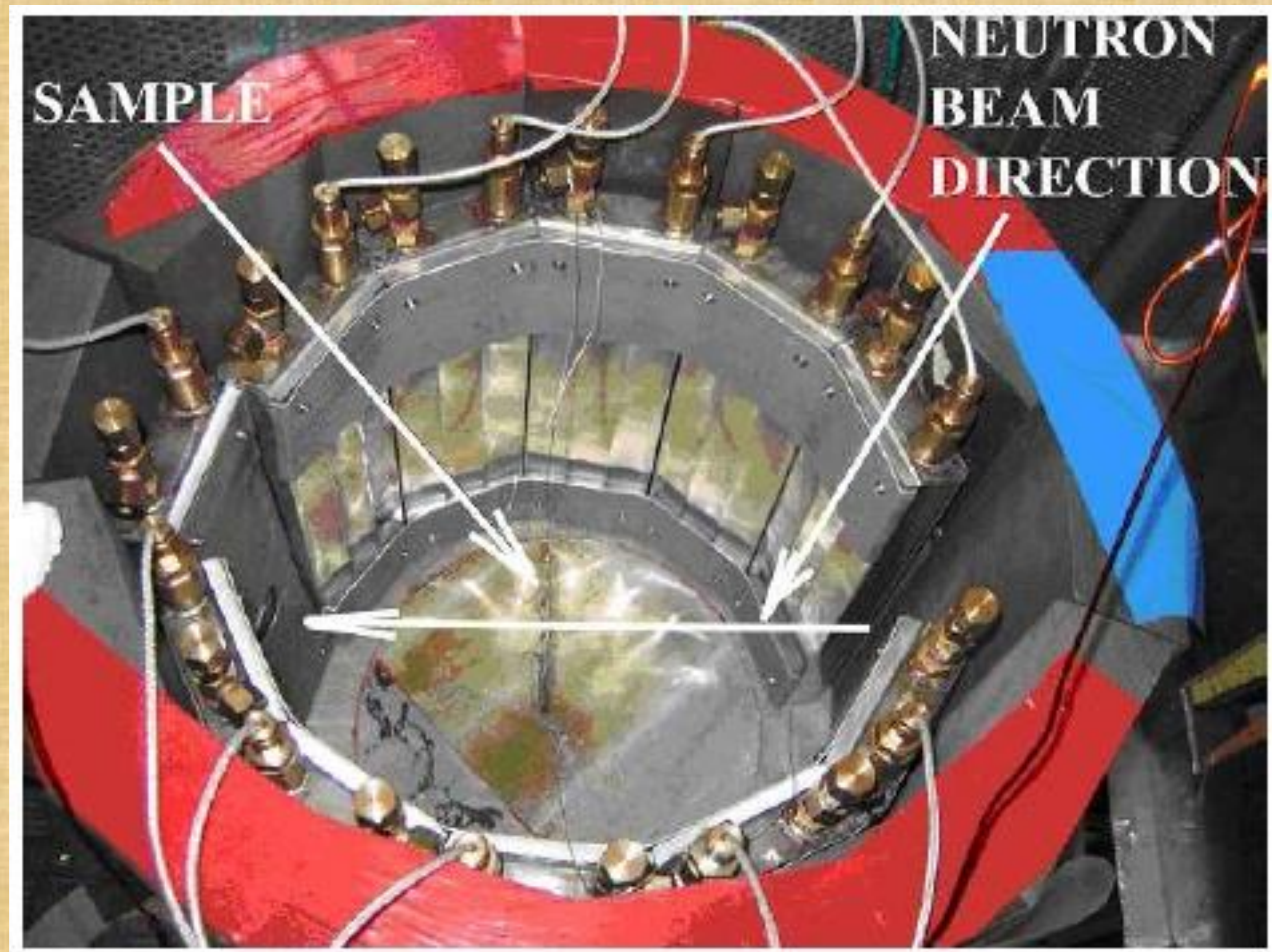


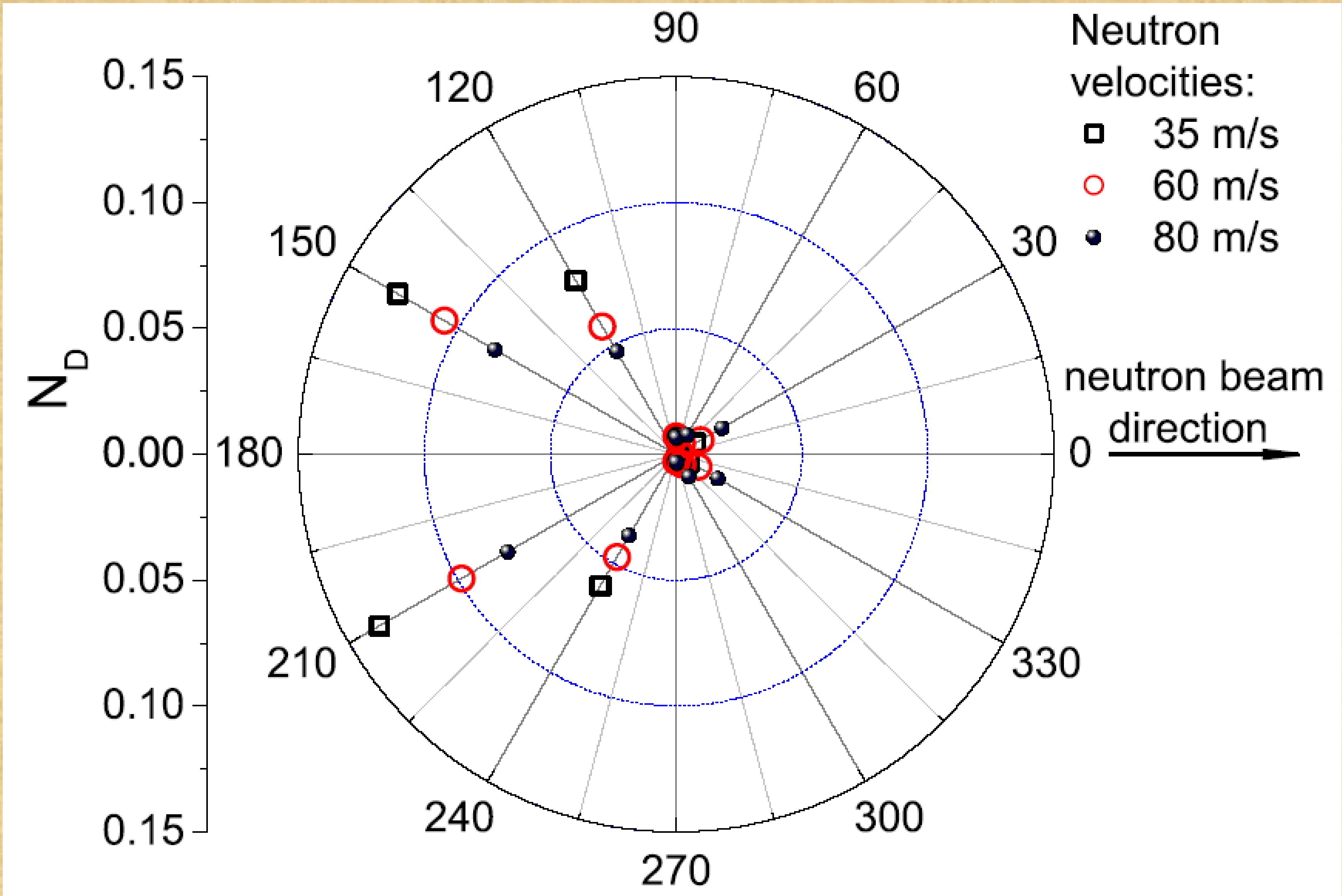
Fig. 1. The experimental setup (view from above).

Neutron scattering on nanoparticles



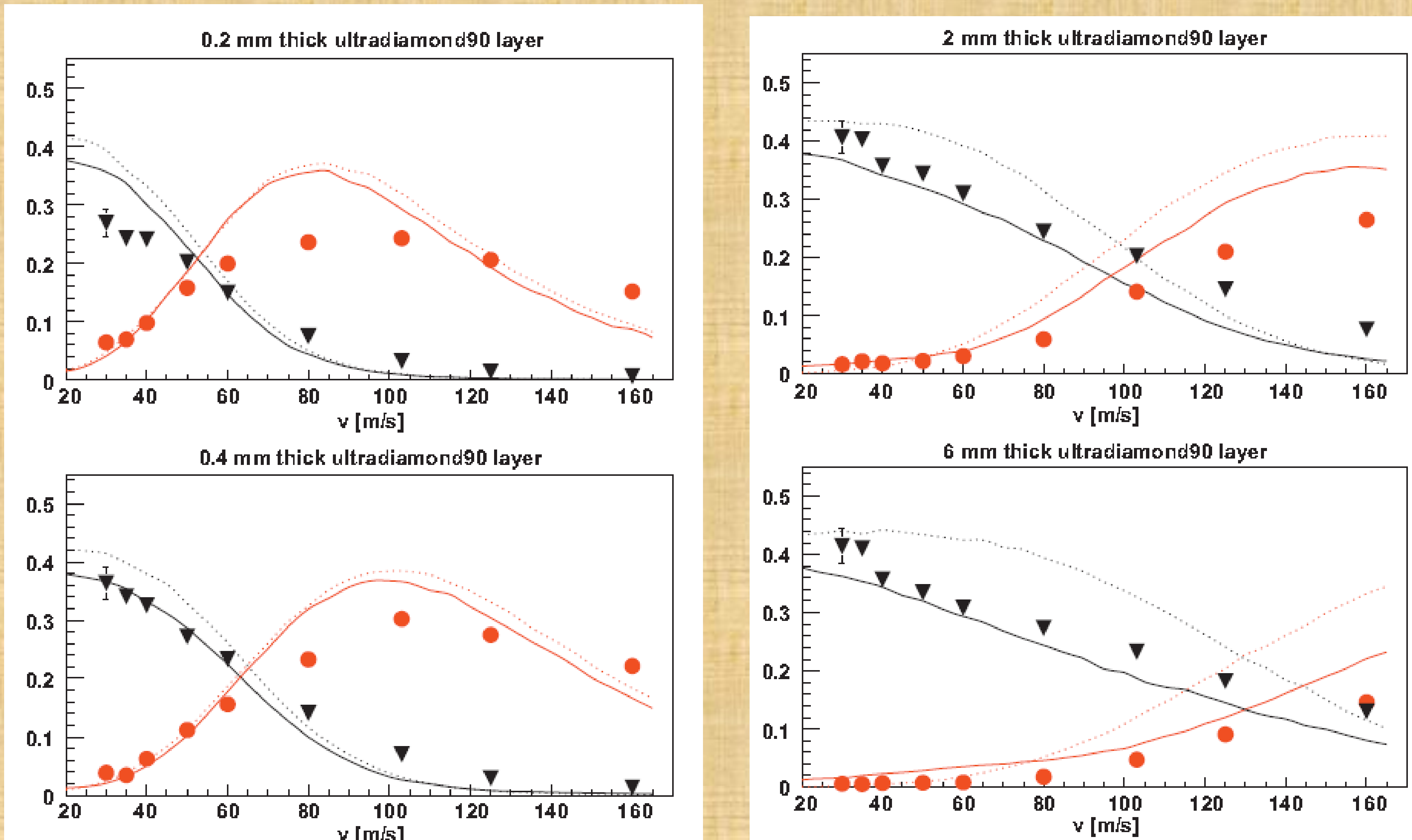
Reflection of very cold neutrons from the powders

Scattering is very efficient !



Reflection of very cold neutrons from the powders

Scattering is very efficient !



Reflection of very cold neutrons from the powders

Scattering is elastic !

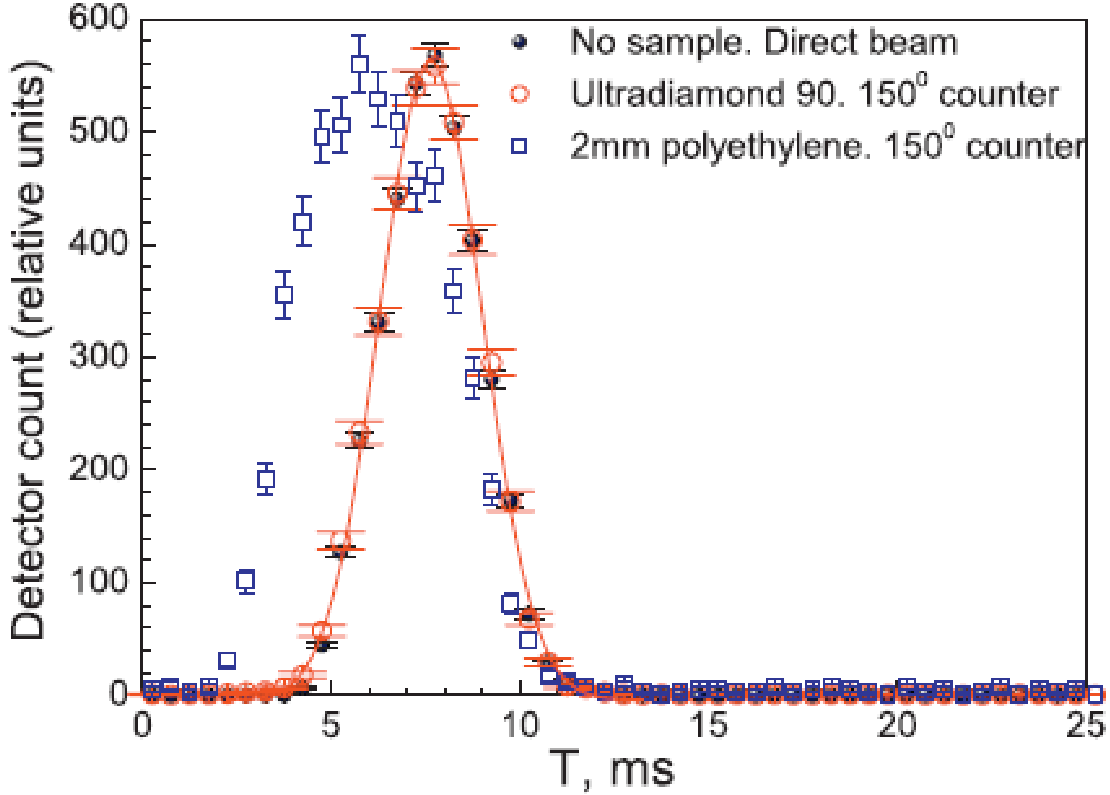
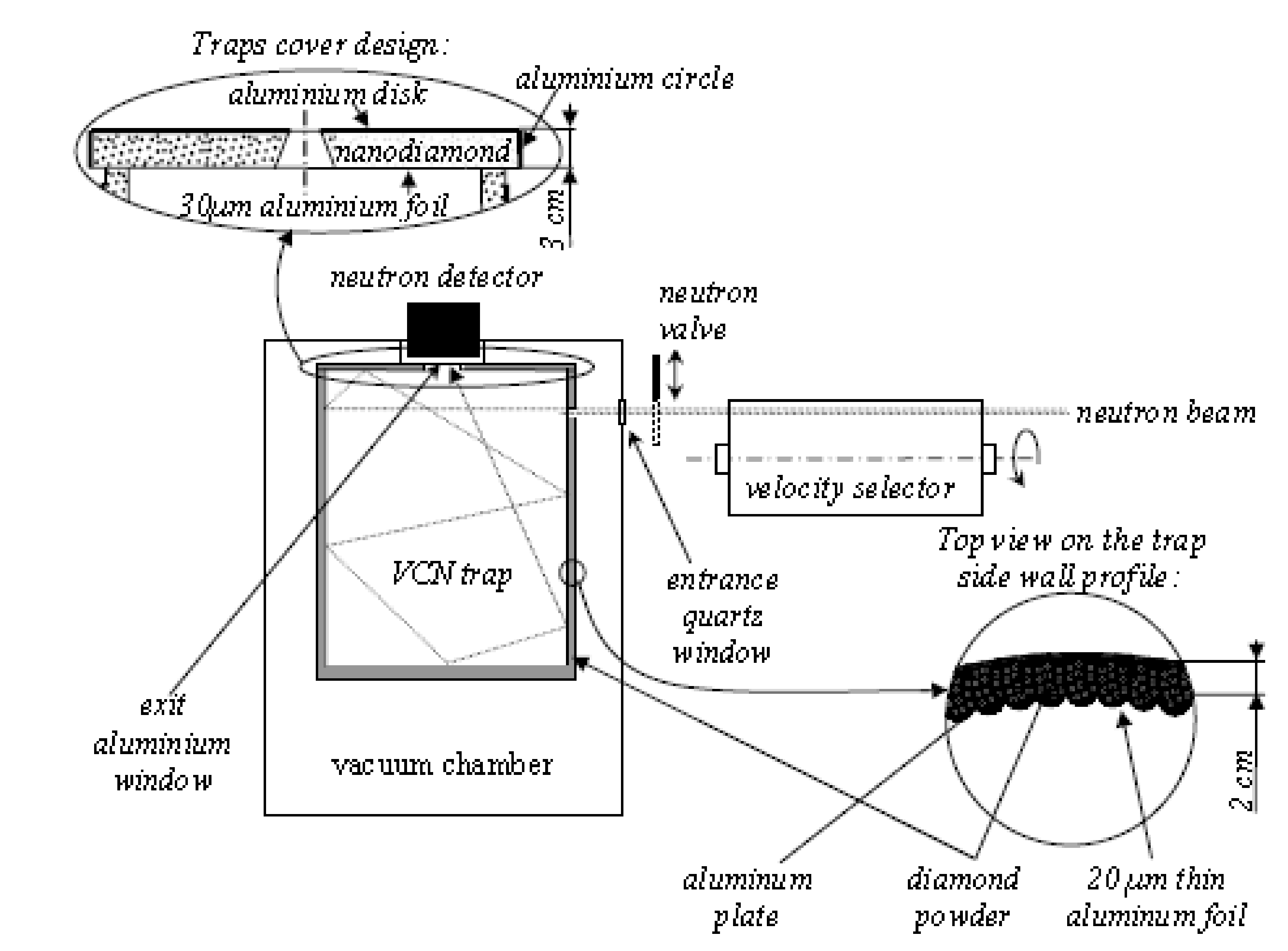


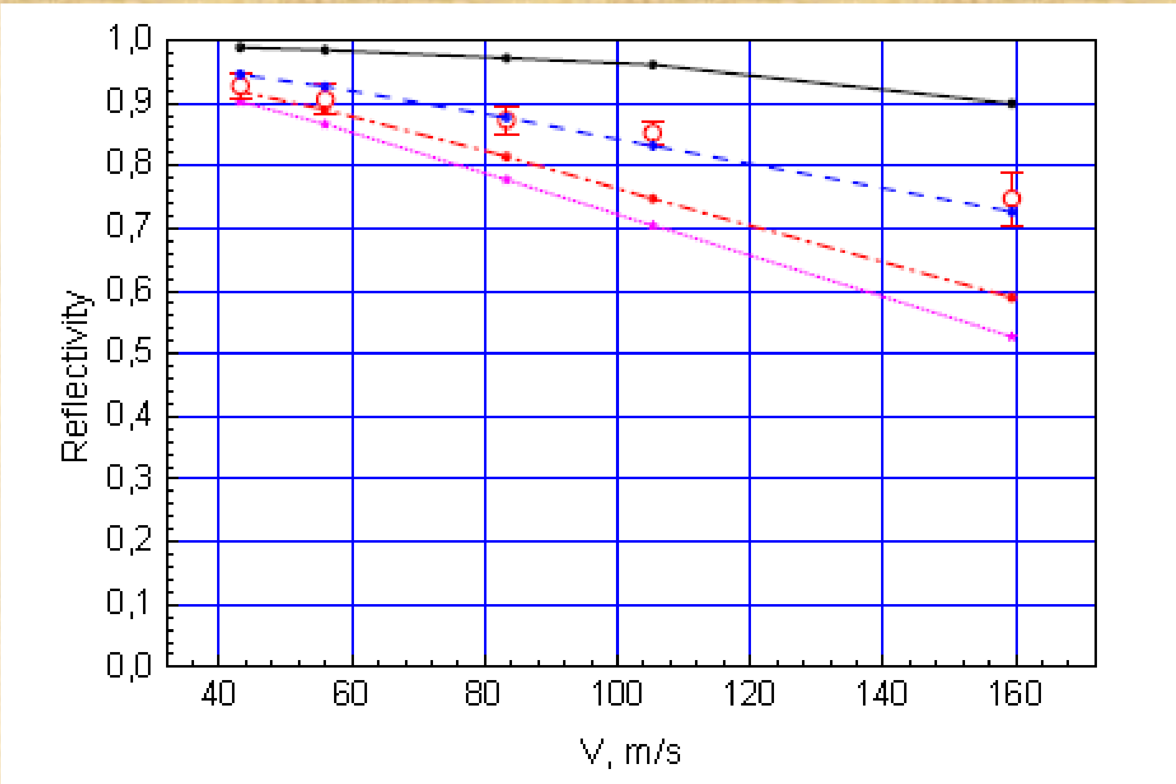
Fig. 6. The neutron count rate is presented as a function of the time of flight of the neutrons with an average initial velocity of 60 m/s. The zero time is synchronized with opening the chopper. The black circles correspond to the initial neutron spectrum. The empty circles indicate the data for the spectrum of neutrons scattered to an angle of 150°. The thickness of the ultradiamond90 powder sample is equal to 2 mm. The squares show results for the scattering of neutrons at a polyethylene sample with a thickness of 2 mm, measured at the same counter.

Storage of very cold neutrons in traps

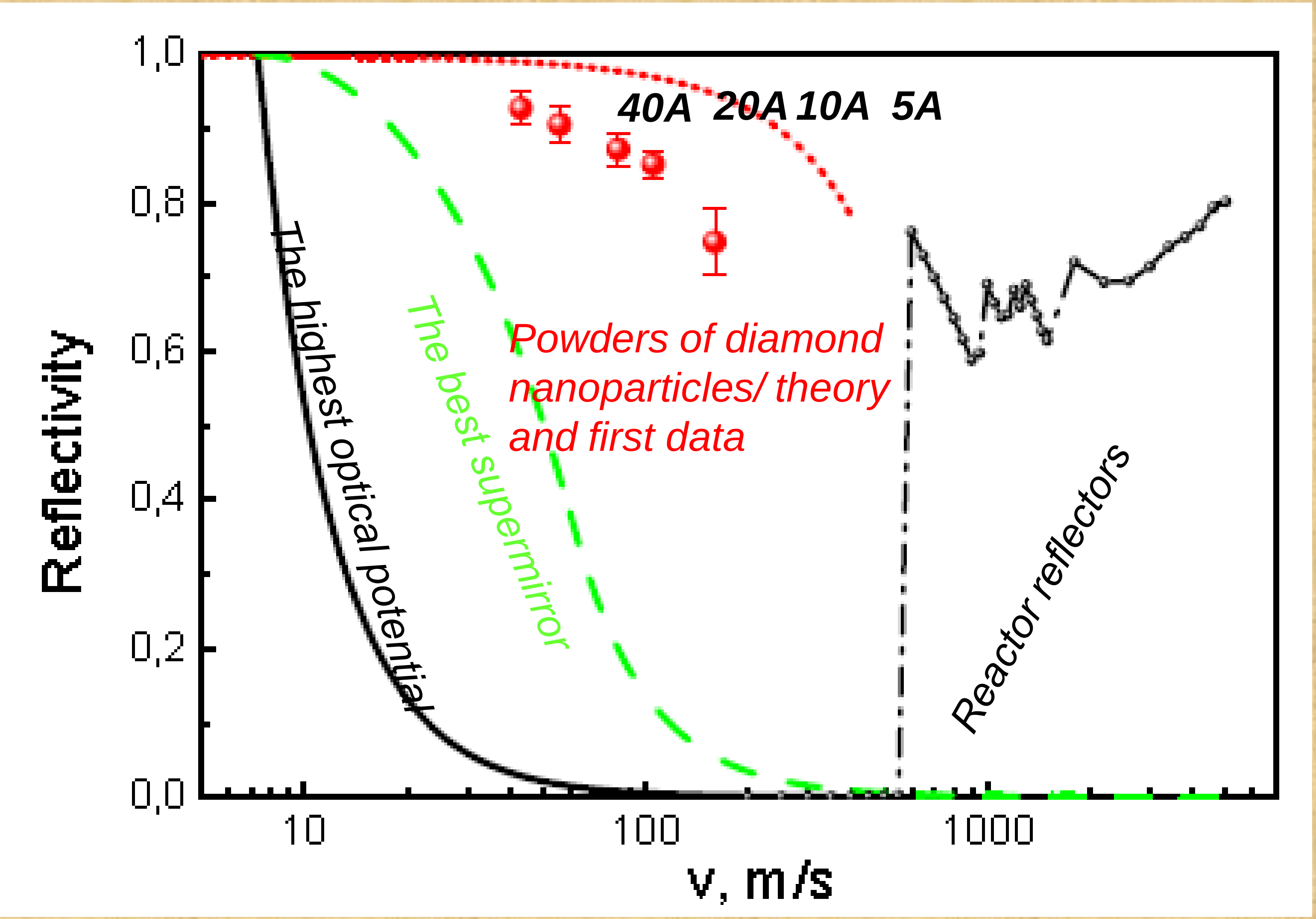


Storage of very cold neutrons in traps

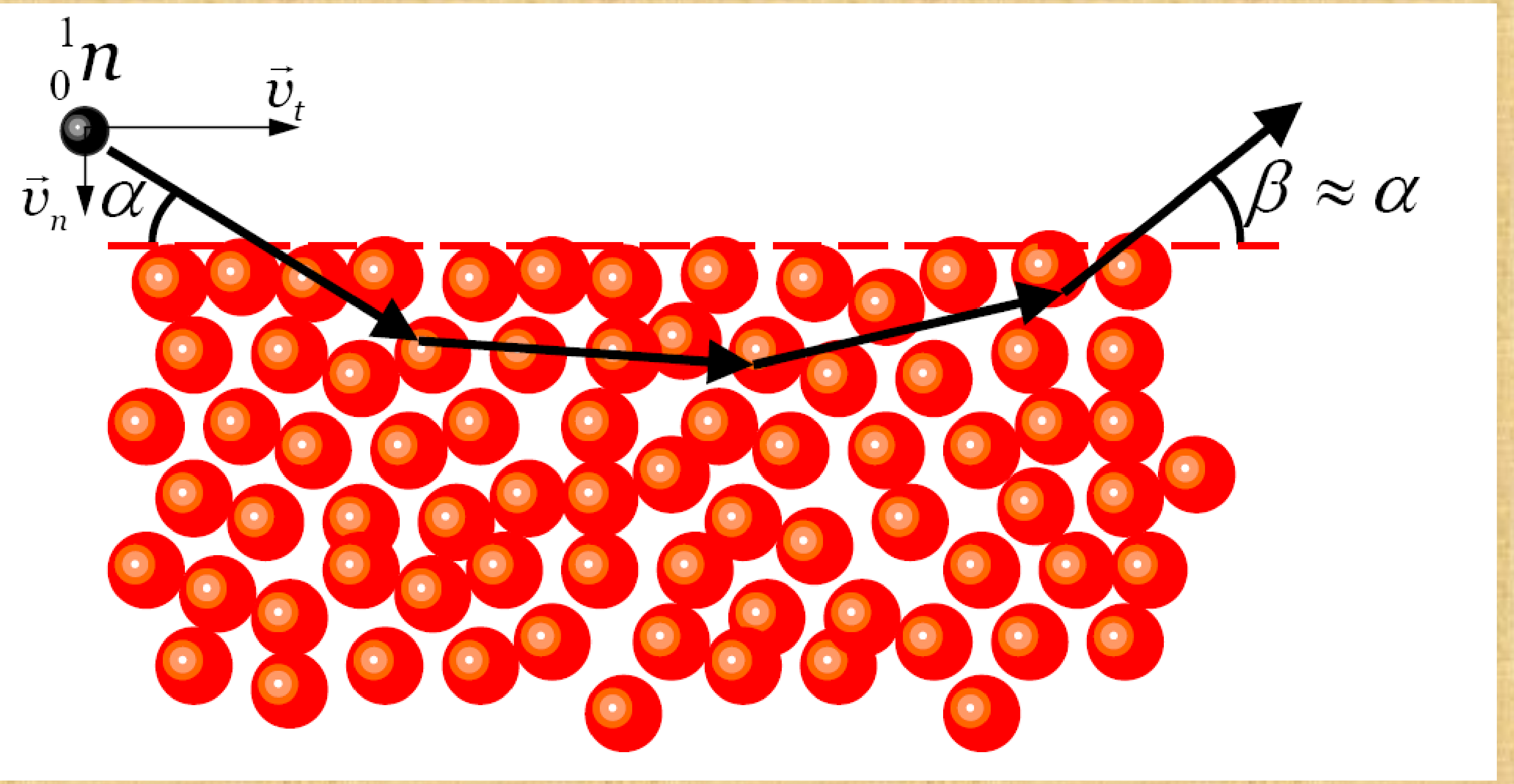
Storage of very cold neutrons in traps



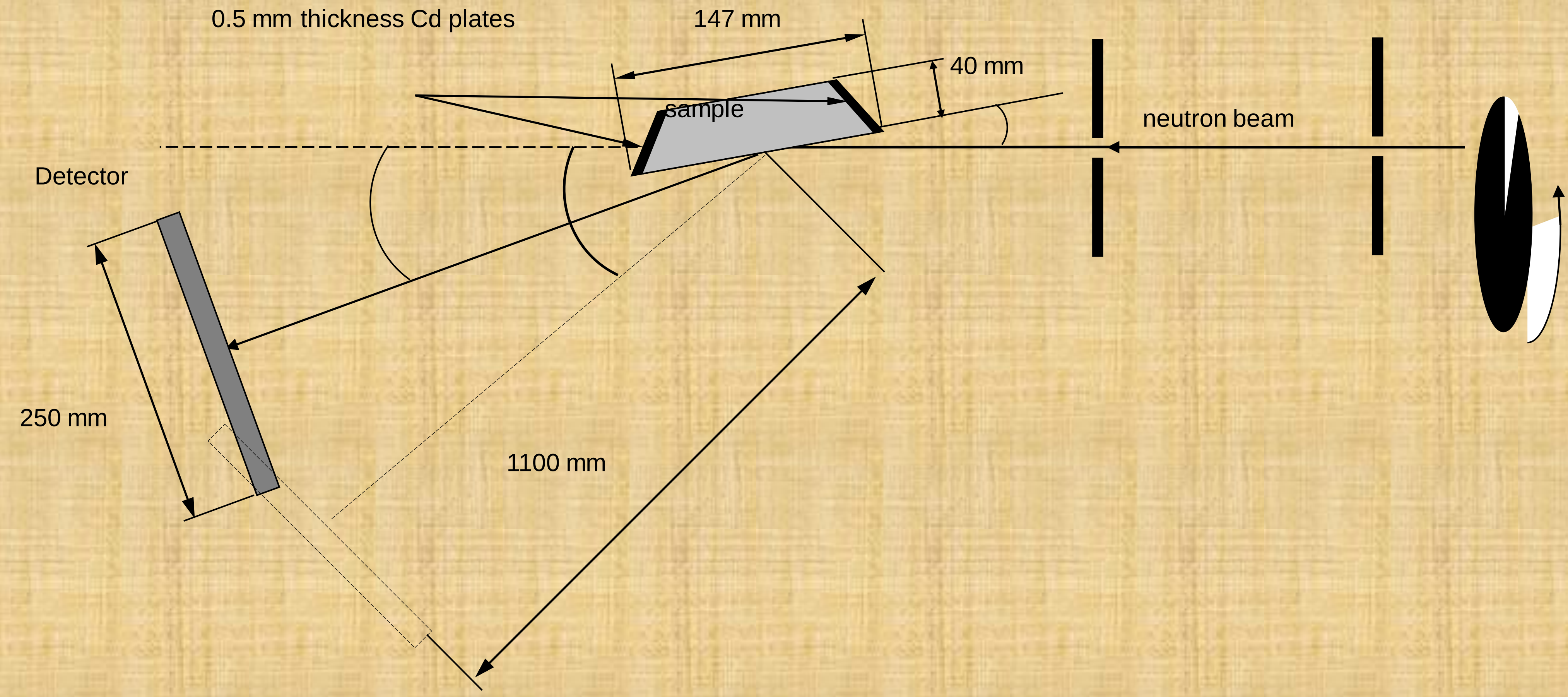
Storage of very cold neutrons in traps



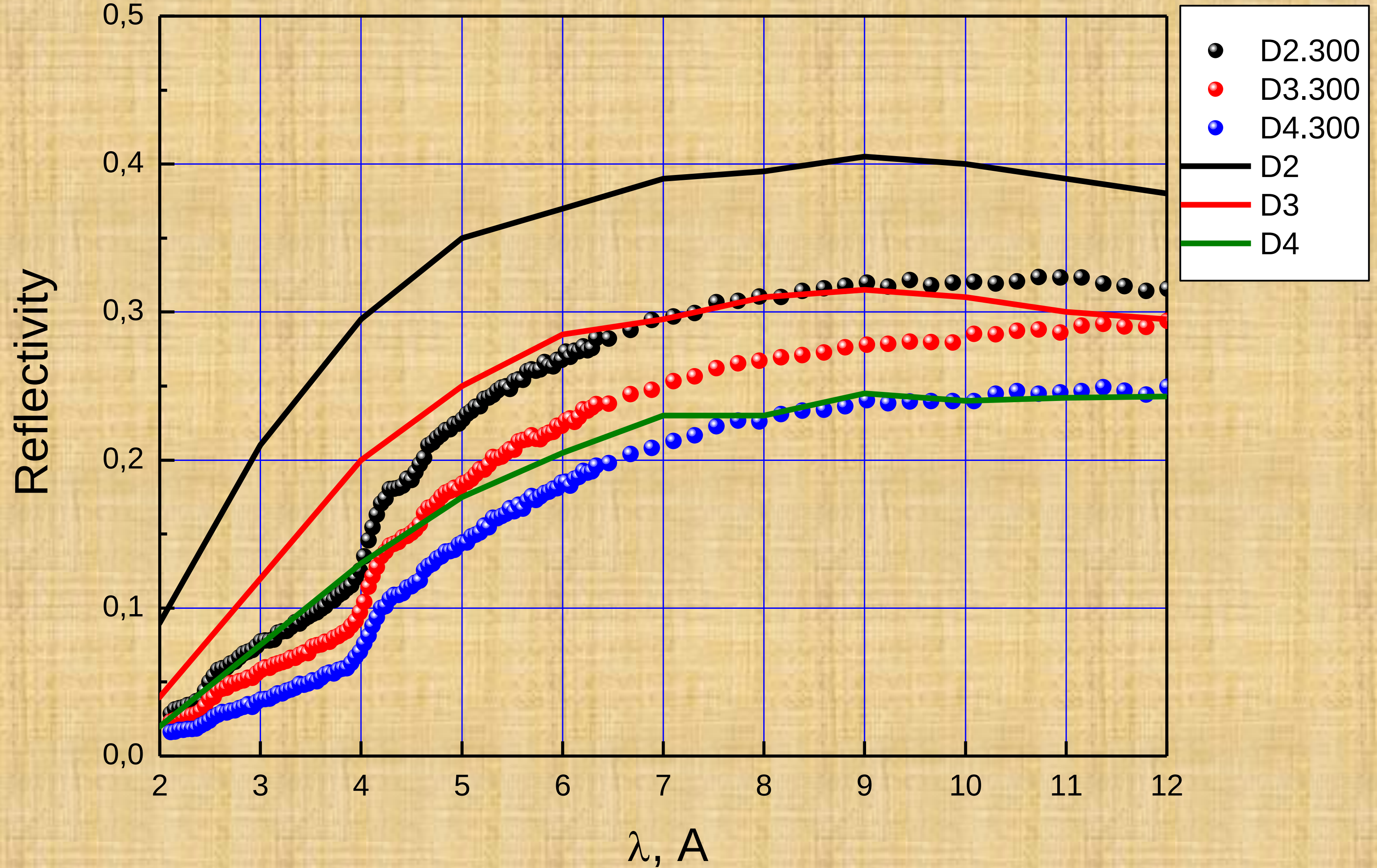
Quasi-specular reflection of cold neutrons from powders



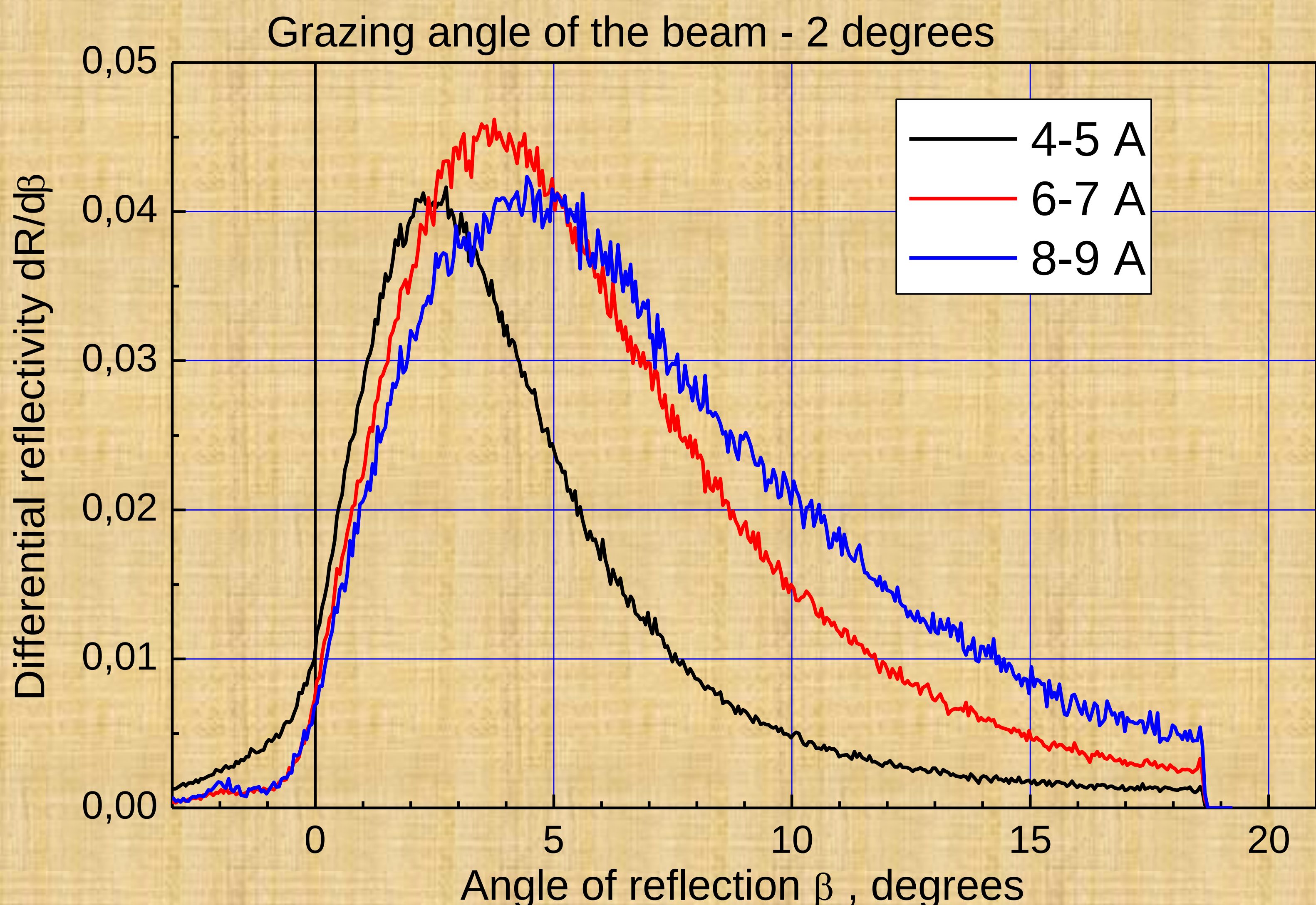
Quasi-specular reflection of cold neutrons from powders



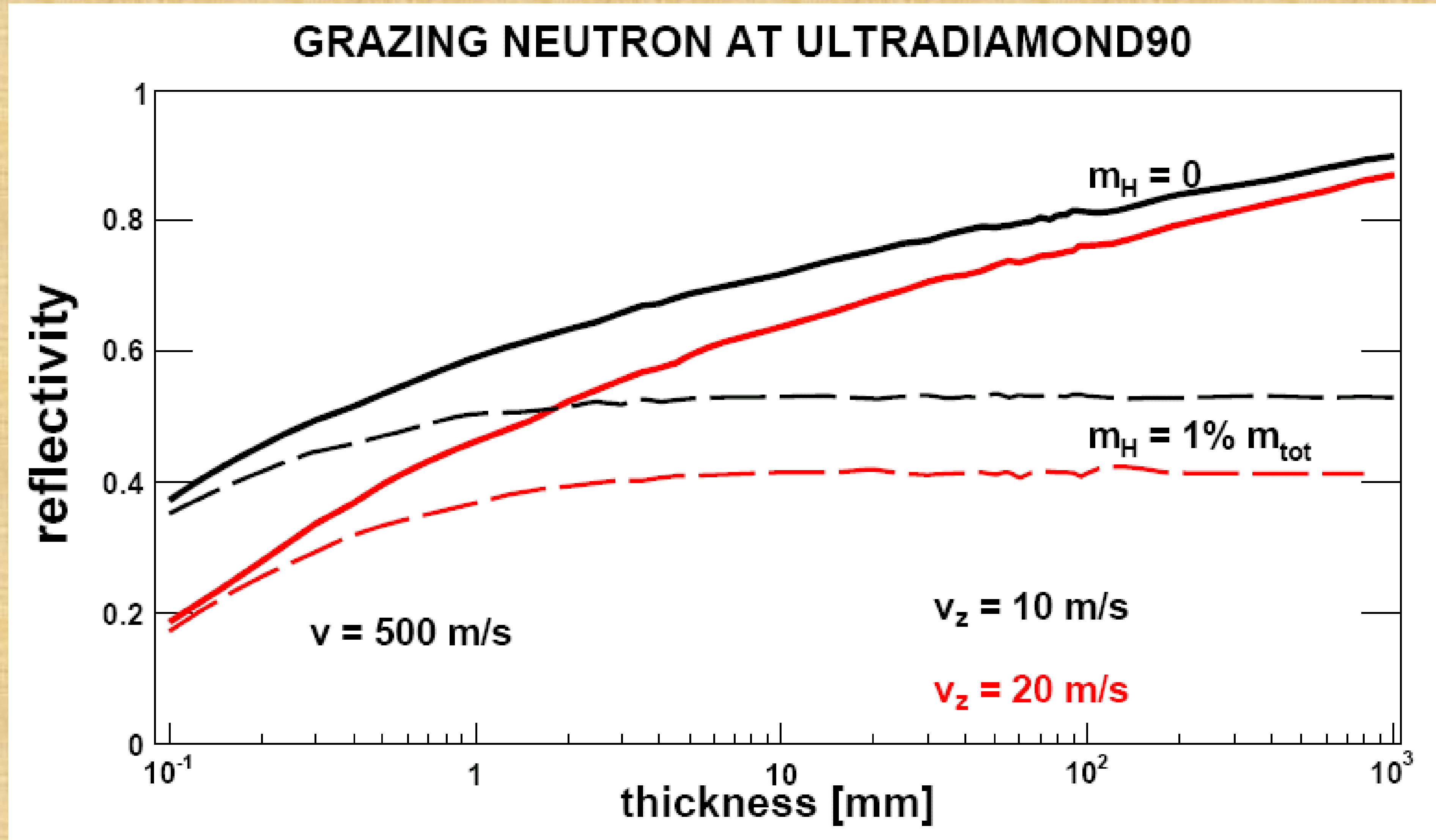
Quasi-specular reflection of cold neutrons from powders



Quasi-specular reflection of cold neutrons from powders



Quasi-specular reflection of cold neutrons from powders



Possible applications

Slow neutrons are traditionally subdivided into several groups in function of their energy/velocity:

- Cold neutrons (CNs): typical velocity 500 m/s; you have a lot of CNs from all typical neutron sources (nuclear reactors and spallation neutrons sources), if they are equipped with a cold liquid-deuterium or liquid-hydrogen source
- Ultracold neutrons (UCNs): typical velocity 5 m/s; in spite of all worldwide efforts extremely low densities available for experiments, however a unique property of total reflection from material and magnetic walls thus storage of UCNs in traps
- Very cold neutrons (VCNs): typical velocity 50 m/s; limited fluxes and no efficient reflectors …until recent years

NEUTRONS FOR SCIENCE

Possible applications

Neutrons of all these mentioned energy ranges (CNs, VCNs, UCNs) are used in numerous experiments in the field of fundamental particle physics.

To mention some examples:

- experiments searching for the electric dipole moment (EDM) of the neutron with the method of storage of UCNs in traps and passage of CNs through non-centrosymmetric crystals,
- precision measurements of the neutron beta-decay: measurements of asymmetry coefficients using CNs and UCNs as well as measurements of the neutron lifetime using UCNs and CNs;
- search for neutron-antineutron oscillations (CNs) and the neutron electric charge (VCNs and UCNs),
- search for fundamental short-range forces using gravitational and centrifugal quantum states of UCNs and CNs, as well as scattering of CNs on noble gases

Possible applications

All these studies would gain if experiments are done with high densities/fluxes of very cold neutrons (VCNs) using both the standard "beam" techniques and the storage of VCNs in traps

New kinds of experiments would emerge

The implementation of nano-powder reflectors is under study at all major facilities in the world as well as within a special IAE

Behavior of nanoparticles in high radiation fluxes

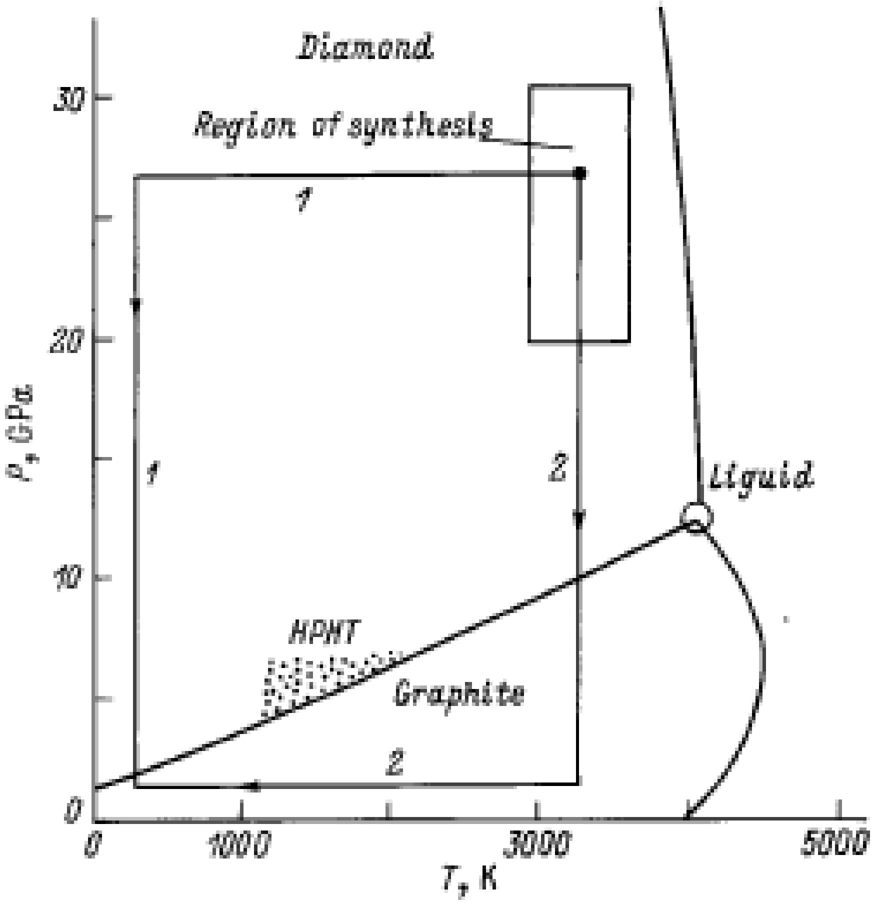


Рис. 1. Фазовая диаграмма углерода и кинетика охлаждени
продуктов детонационного синтеза для двух идеализированны
случаев: скорость охлаждения много больше (1) и много мень
ше (2) скорости падения давления

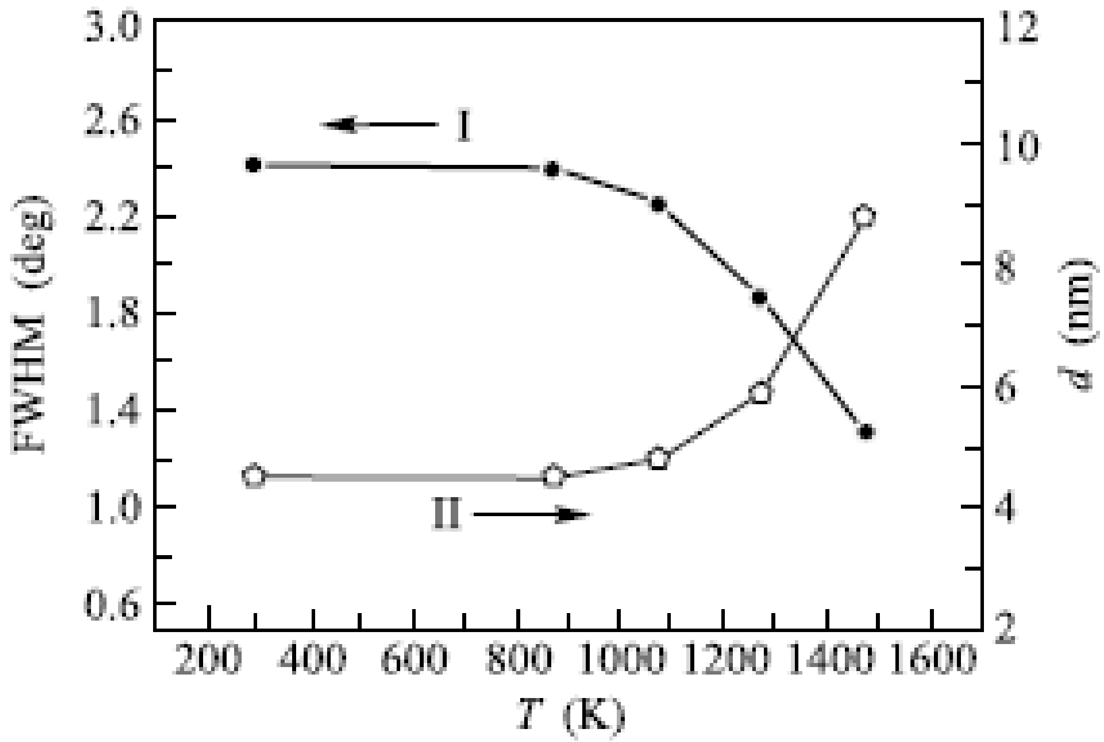


Рис.2. Температурные зависимости ширины дифракционного пика (111) алмаза (I) и среднего размера алмазных частиц (II), полученных в результате обработки исходного порошка НА со средним размером частиц 4.5 нм при 8 ГПа

CONCLUSION

- Powders of diamond nanoparticles provide the first efficient reflectors for very cold neutrons
- Powders of diamond nanoparticles provide efficient quasi-specular reflection of cold neutrons (down to the Bragg wavelength)
- Such powders could provide a major gain in fluxes and densities of slow neutrons in various configurations
- High resistance of diamond nanoparticles at least in moderate radiation fluxes has been verified
- Absorption of neutrons in diamond nanoparticles is dominated by hydrogen admixtures; the amount of hydrogen could be significantly reduced by proper powder treatment and conditioning
- Alternative materials (even lower absorption) and nanoparticle parameters (nanorods) could be studied in order to improve even further the reflective properties of nano-powders

Bonus

Equilibrium cooling of very cold neutrons in gels of ultracold (1 mK) weakly bound (for instance impurity gels in superfluid helium) nanoparticles.

Analogue: billiard-ball collisions of neutrons with nuclei in reactor moderators.

Evident difficulty: ultralow temperatures, ultra-weak interactions

Potential gain: a gain of many orders of magnitude in the efficiency of UCN production

Nanoparticles/nanodroplets "levitating" in vicinity of surfaces.

New universal phenomenon.

Systematical effects in precision experiments with UCNs (like measurements of the neutron lifetime with UCNs)

Sensitive probe of surface potentials.

Difficult to find alternative experimental methods.