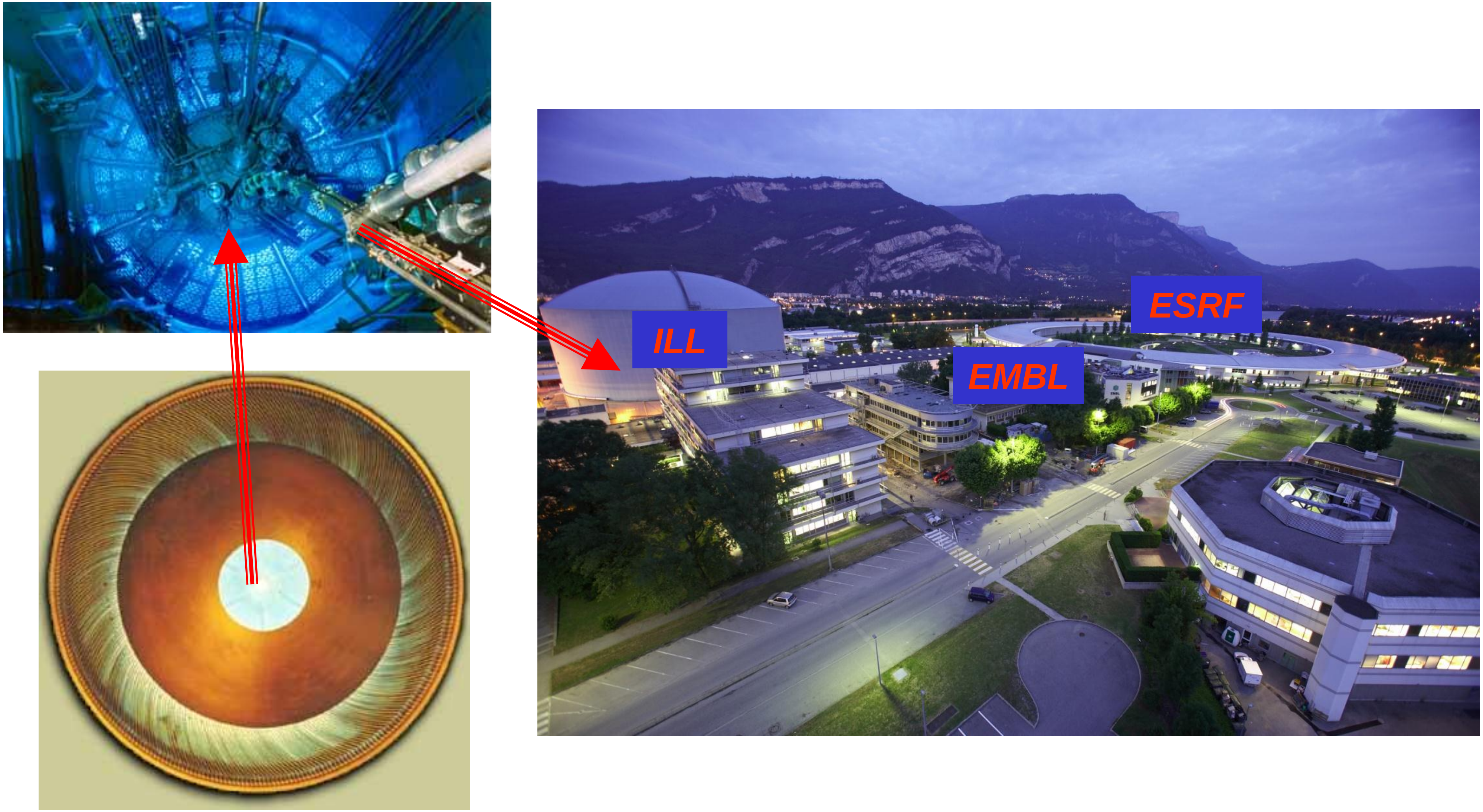
High-flux ILL reactor



Experimental neutron facility

Institut Laue-Langevin (ILL), Grenoble, France
World Leader in Neutron Research (Condensed matter, Magnetism, Chemistry, Biology, Crystallography, Materials, Nuclear and Particle Physics)

Experimental neutron facility

At ILL: ~450 staff members, including ~70 scientists, ~20 Ph.D. students.

~~4~~ scientists in fundamental physics; ~~4~~ scientists in nuclear physics…

1.5 **1.5**

=> COLLABORATIONS!!!

3000 visiting scientists per year

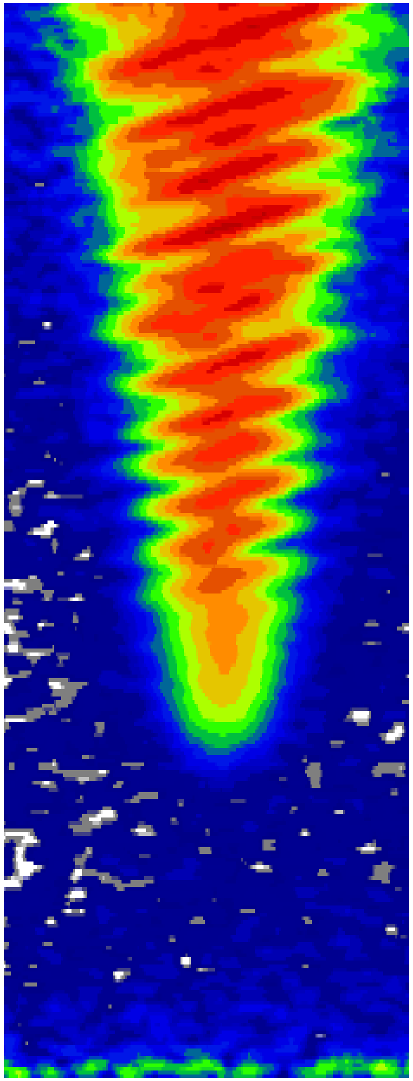
GRANIT-2010 Workshop
14-19 February 2010, Les Houches, France

Granit
Gravitational Neutron Induced Transitions

1. Gravitational quantum states of neutrons

2. GRANIT project

3. Centrifugal quantum states of neutrons



Gravitational quantum states of neutrons

Quantum states of neutrons in the Earth's gravitational field

Valery V. Nesvizhevsky*, Hans G. Börner*, Alexander K. Petukhov*, Hartmut Abele†, Stefan Baeßler†, Frank J. Rueß†, Thilo Stöferle†, Alexander Westphal†, Alexei M. Gagarski‡, Guennady A. Petrov‡ & Alexander V. Strelkov§

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† *University of Heidelberg, 12 Philosophenweg, Heidelberg D-69120, Germany*
‡ *Petersburg Nuclear Physics Institute, Orlova Roscha, Gatchina, Leningrad reg. R-188350, Russia*
§ *Joint Institute for Nuclear Research, Dubna, Moscow reg. R-141980, Russia*

The discrete quantum properties of matter are manifest in a variety of phenomena. Any particle that is trapped in a sufficiently deep and wide potential well is settled in quantum bound states. For example, the existence of quantum states of electrons in an electromagnetic field is responsible for the structure of atoms[16], and quantum states of nucleons in a strong nuclear field give rise to the structure of atomic nuclei[17]. In an analogous way, the gravitational field should lead to the formation of quantum states. But the gravitational force is extremely weak compared to the

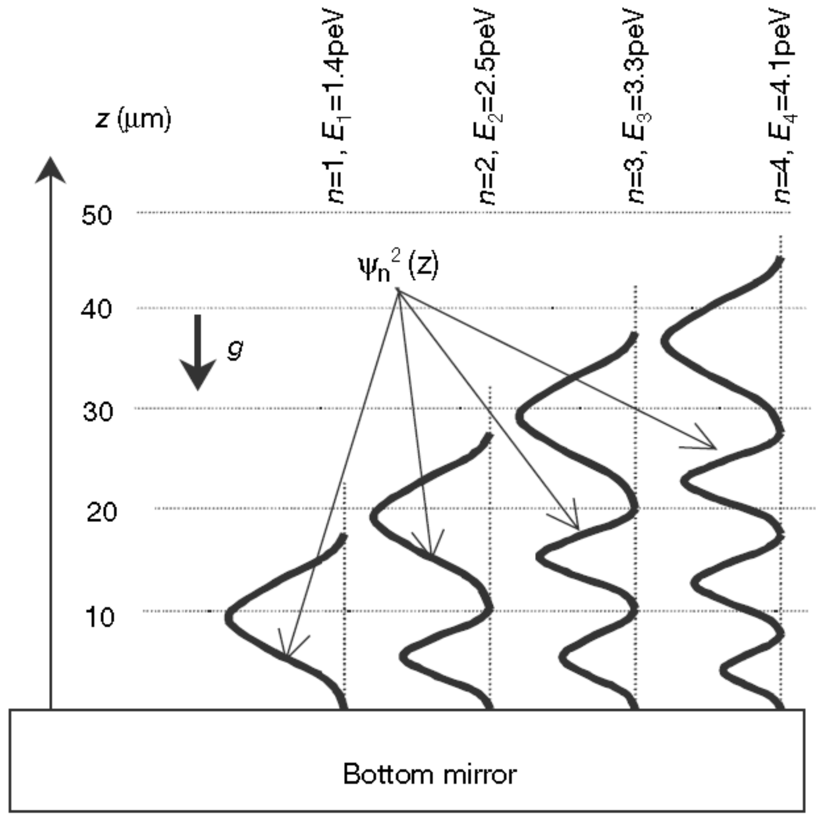
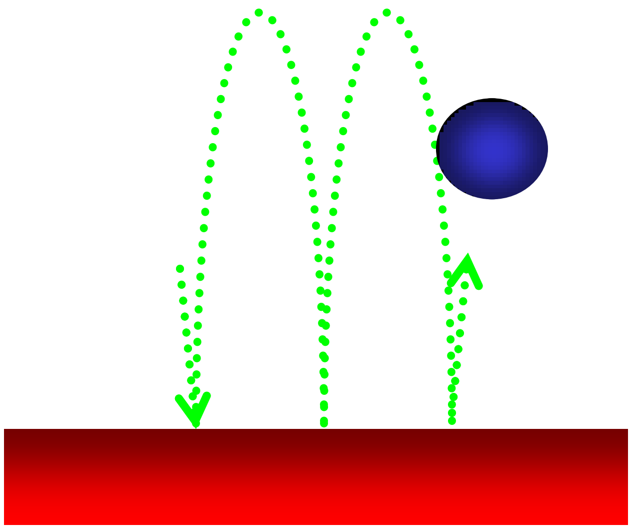


Figure 1 Wavefunctions of the quantum states of neutrons in the potential well formed by the Earth's gravitational field and the horizontal mirror. The probability of finding neutrons at height z, corresponding to the nth quantum state, is proportional to the square of the neutron wavefunction $\psi_n^2(z)$. The vertical axis z provides the length scale for this phenomenon. E_n is the energy of the nth quantum state.

Choosing a quantum system



1) ***Electrical neutrality*** ***(usually gravitational interaction of an object with surface is much weaker than other interactions)***

2) ***Long life-time*** $\left(\Delta E \approx \frac{\hbar}{\Delta \tau} \right)$

3) ***Small mass*** $\left(\Delta v \cdot \Delta x \approx \frac{\hbar}{m} \right)$

4) ***Energy (effective temperature) of UCN is extremely low; it is not equal to the surface temperature (the temperature of neutrons in gravitational quantum states is ~10^{-8}K)***

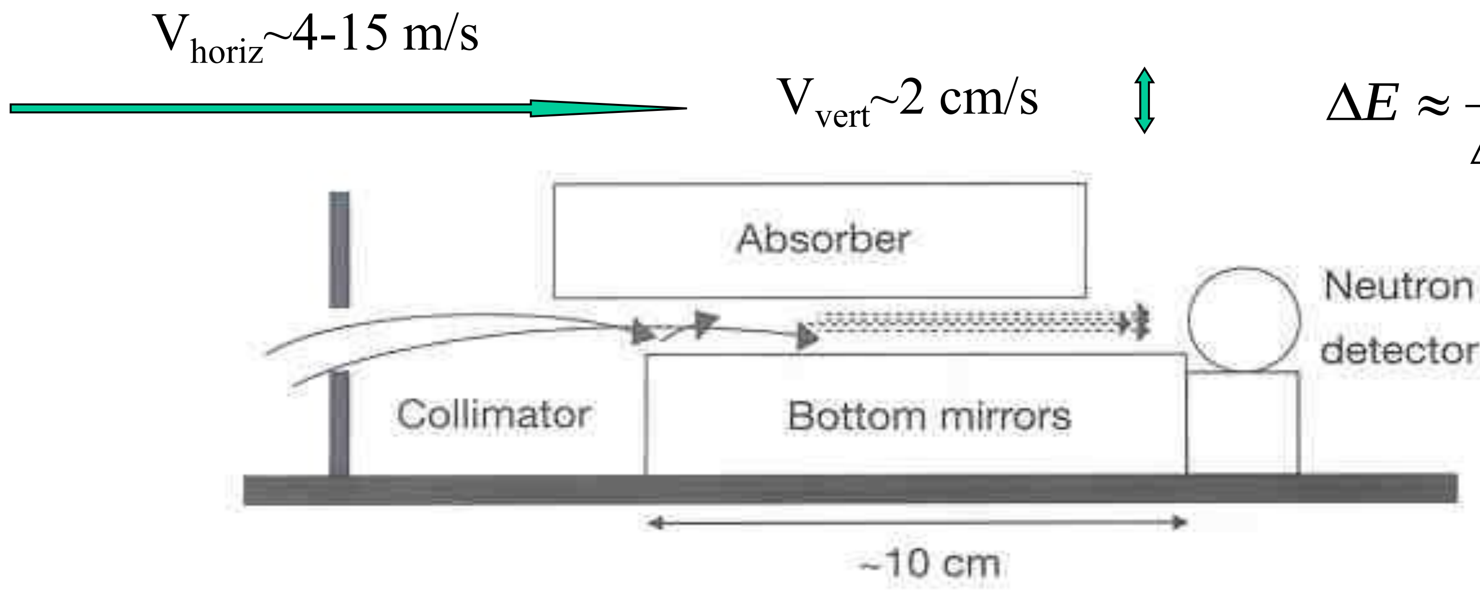
Neutron avobe mirror in gravity field

(mirror represents nearly infinitely high and sharp potetial step)

Energy of quantum states, in Bohr-Zommerfeld approximation, equals :

$$E_n \approx \sqrt[3]{\left(\frac{9 \cdot m_n}{8}\right) \cdot \left(\pi \cdot \hbar \cdot g \cdot \left(n - \frac{1}{4}\right)\right)^2}$$

Experimental installation and method



$$\Delta E \approx \frac{\hbar}{\Delta \tau}$$

Selection and measurement of vertical and horizontal components of neutron velocity:

Maximum vertical velocity is defined by height of scatterer/absorber above mirror

The range of horizontal neutron velocities is defined by relative position of plates in the entrance collimator and the slit between mirror and scatterer

Experimental installation and method
Model of tunneling through gravitational barrier

$$\xi >> 1$$

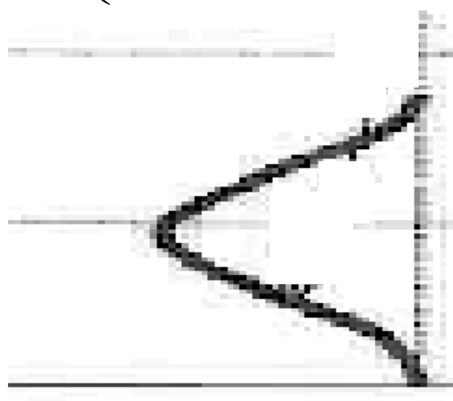
$$\Gamma_n(\xi) = \omega_n \cdot D(\xi) \qquad \omega_n \approx (E_{n+1} - E_n)/\hbar$$

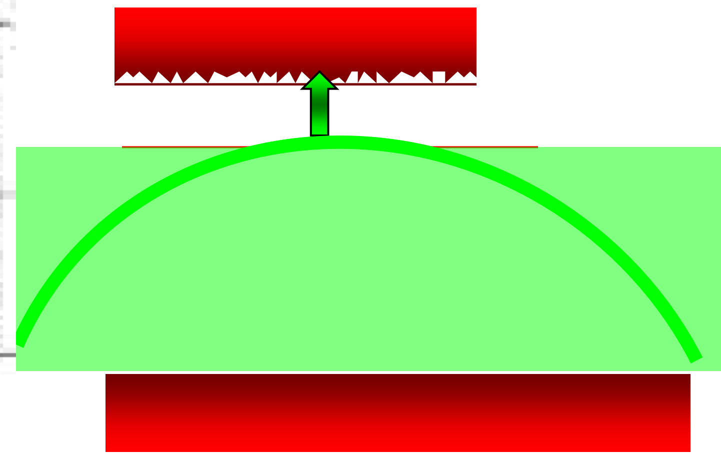
$$D(\xi) \approx Exp[-\frac{4}{3} \cdot \xi^{\frac{3}{2}}],$$

$$P_n(\xi) = Exp(-\Gamma_n(\xi) \cdot \tau)$$

$$F(\Delta z, V_{hor}) = \sum_n \left(\beta_n \cdot Exp\left(-\alpha \cdot \frac{L}{V_{hor}} \cdot C_n^2 \cdot Exp\left(-\frac{4}{3} \cdot \left(\frac{\Delta z - z_n}{z_0} \right)^{\frac{3}{2}} \right) \right) \right)$$

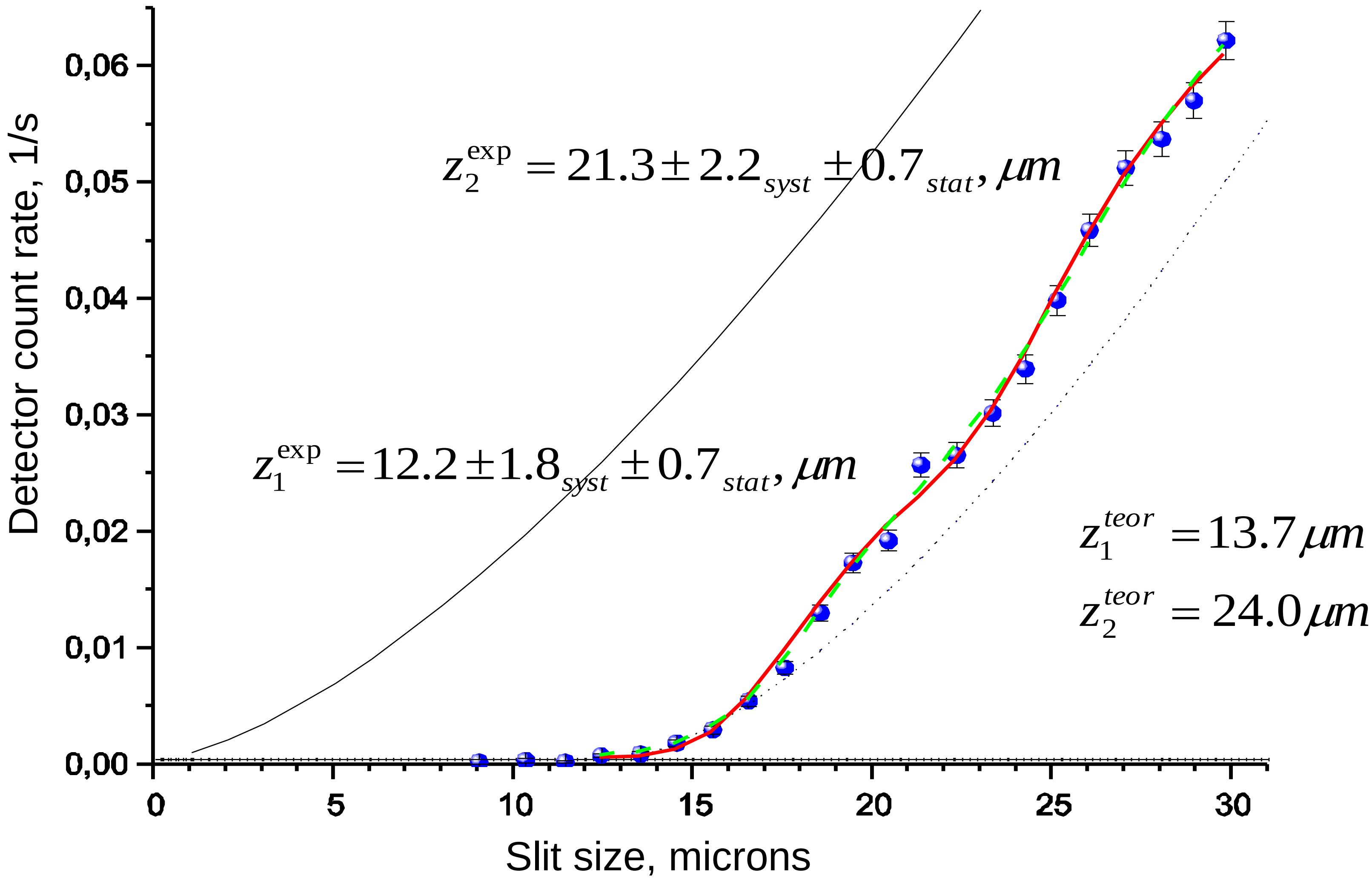
$$D(\xi) = \begin{cases} 1, \xi < 0 \\ A_n \cdot Exp[-\frac{4}{3} \cdot \xi^{\frac{3}{2}}], \xi \end{cases}$$





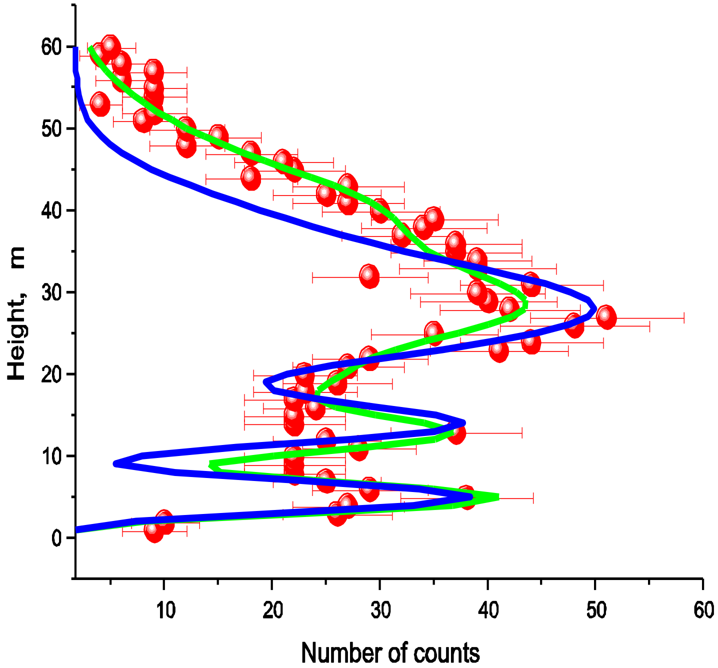
$$P_n(\xi) = Exp(-\Gamma_n(\xi) \cdot \frac{L}{V_{hor}})$$

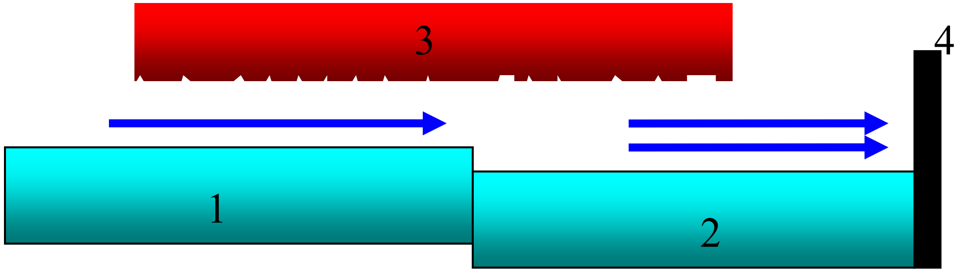
« Integral » method; soft spectrum



« Differential » method, position-sensitive detectors

A method to increase the spatial variation of neutron density





« Differential » method, position-sensitive detectors

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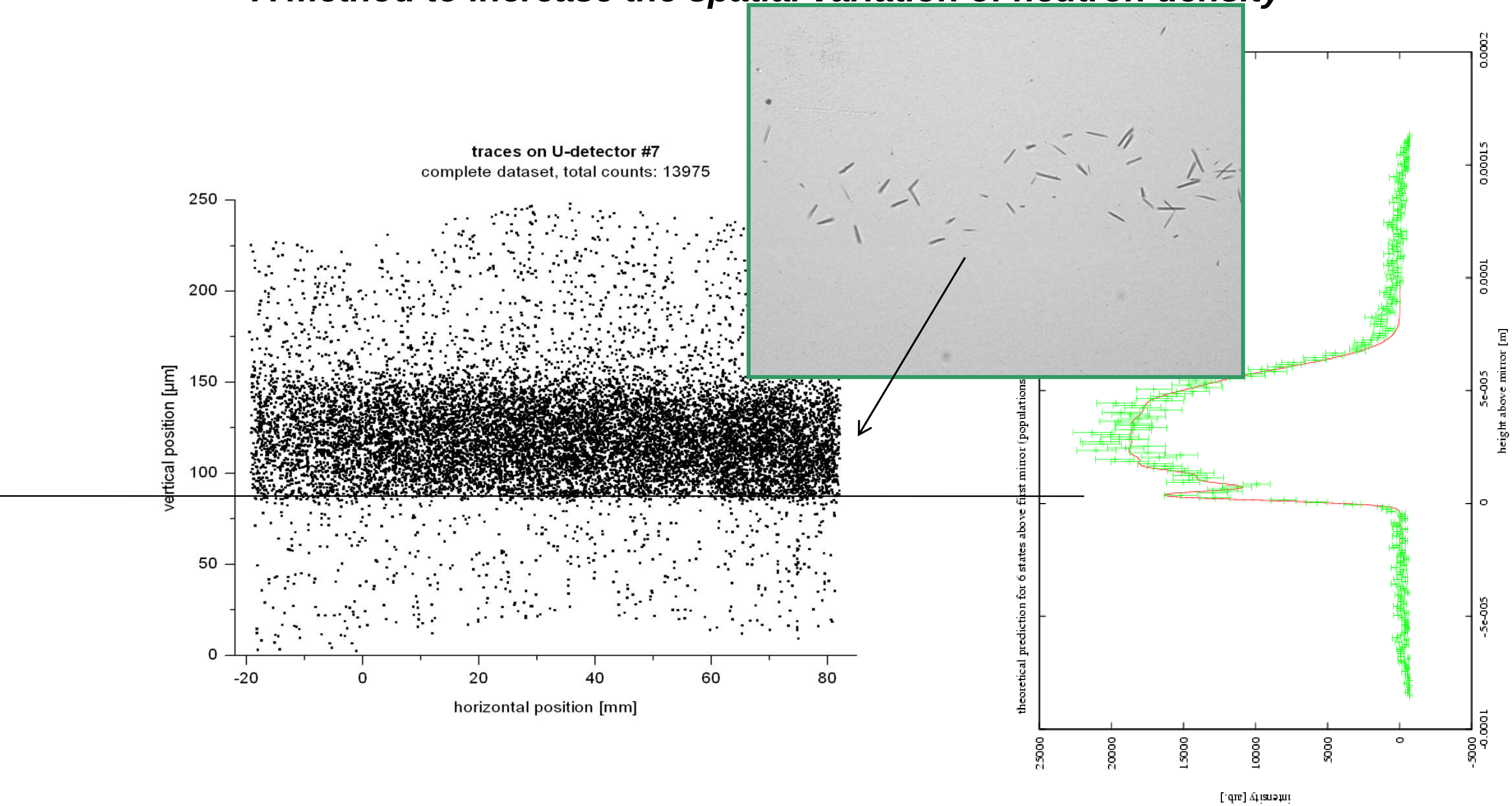


Transitions between gravitational quantum states

Remember: flow-through mode; modest energy resolution

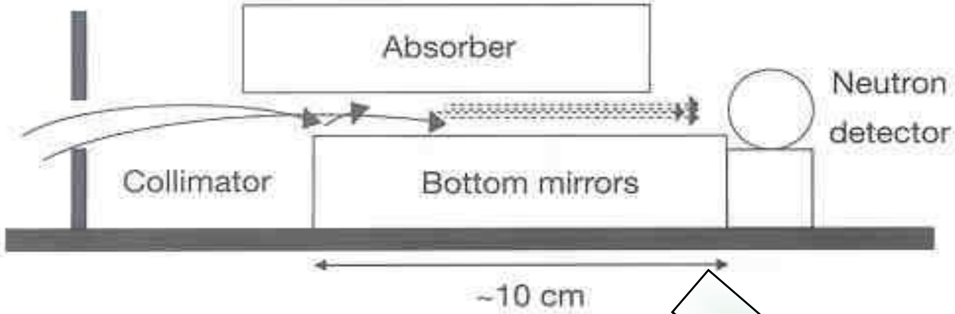


Figure 2 Layout of the experiment. The limitation of the vertica[illegible] component depends on the relative position of the absorber and mirror. To limit th[illegible]ntal velocity component we use an additional entry collimator. The relative height and [illegible] the entry collimator can be adjusted.

Transitions could be excited, for instance:

- By periodically varying magnetic field gradient;

-By periodically varying local gravitational field;

-By oscillating the mirror (periodic variation of optical nuclear potential)

Now: storage mode, long observation time and high energy resolution

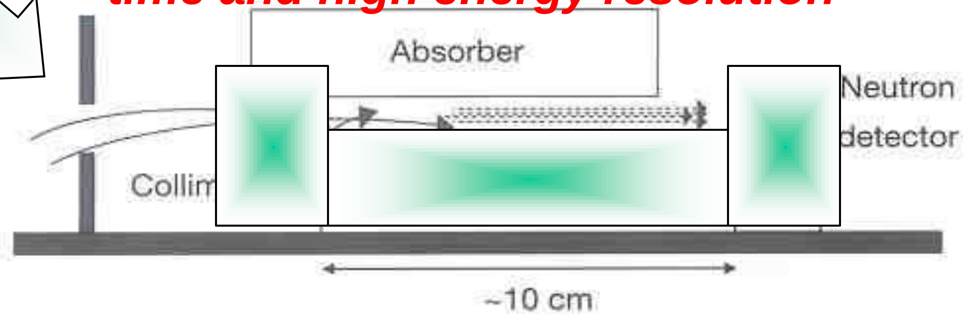
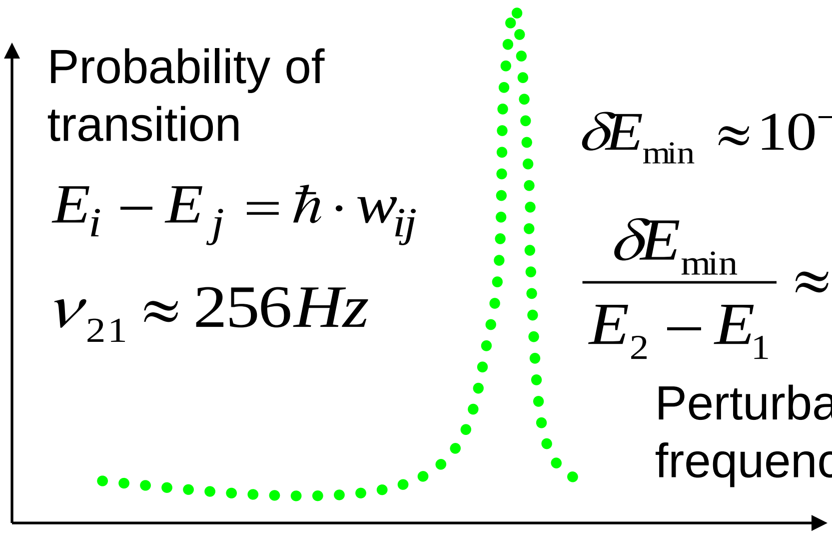


Figure 2 Layout of the experiment. The limitation of the vertical velocity component depends on the relative position of the absorber and mirror. To limit the horizontal velocity component we use an additional entry collimator. The relative height and size of the entry collimator can be adjusted.



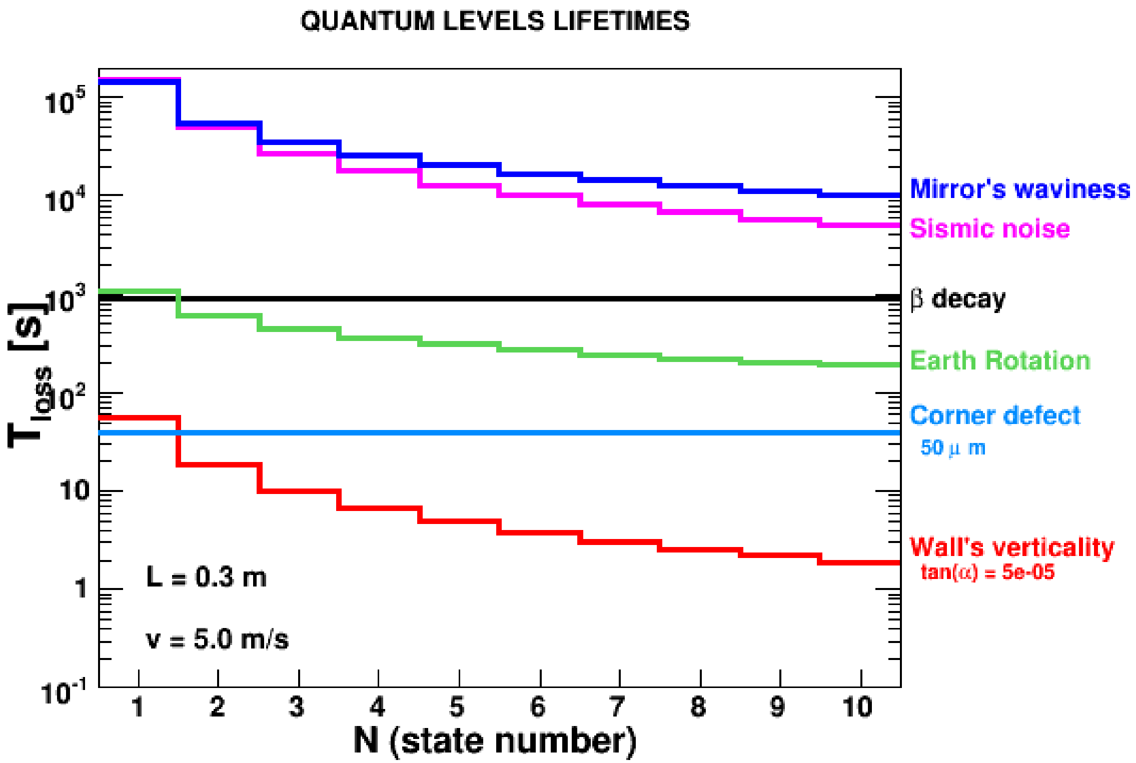
$$E_i - E_j = \hbar \cdot w_{ij}$$

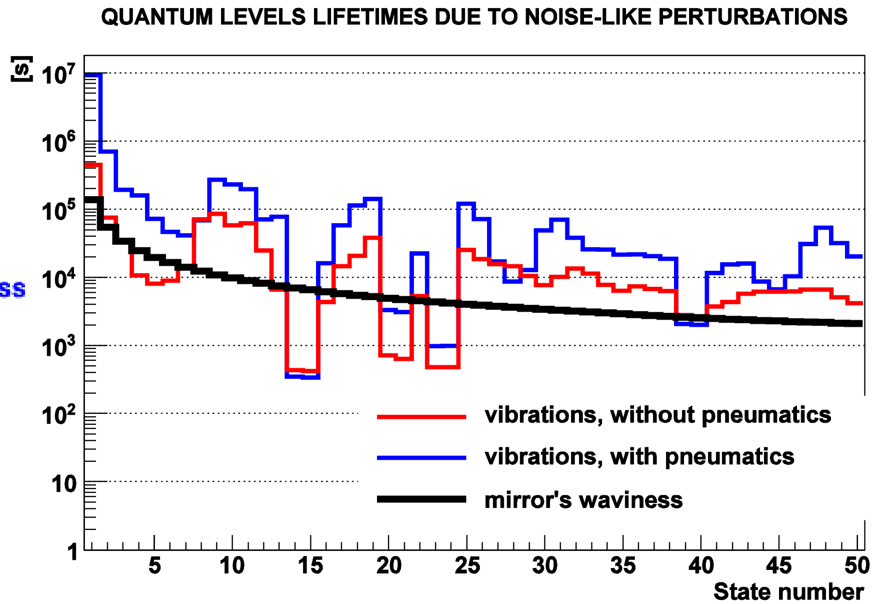
$$\nu_{21} \approx 256 Hz$$

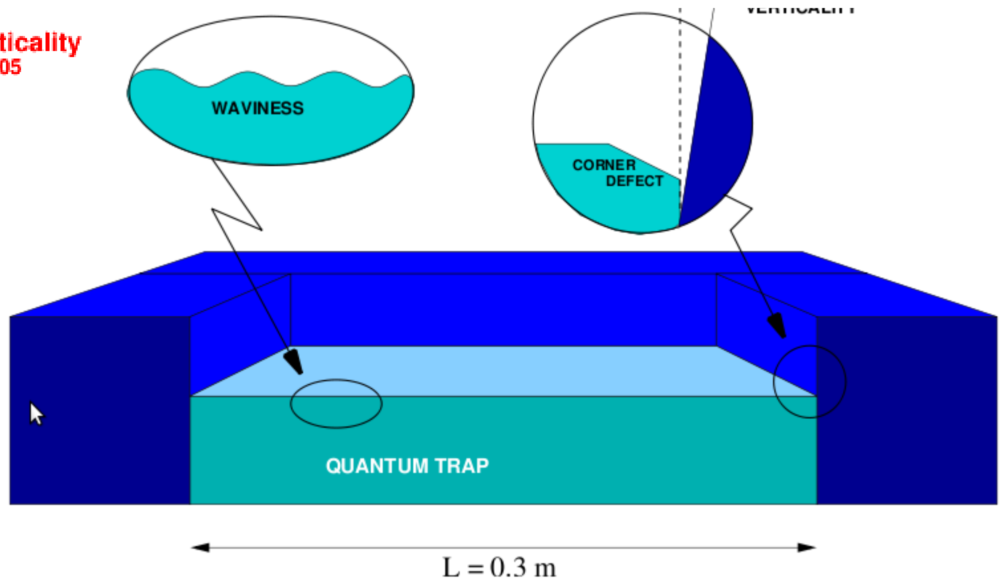
$$\delta E_{\min} \approx 10^{-18} eV$$

$$\frac{\delta E_{\min}}{E_2 - E_1} \approx 10^{-6}$$

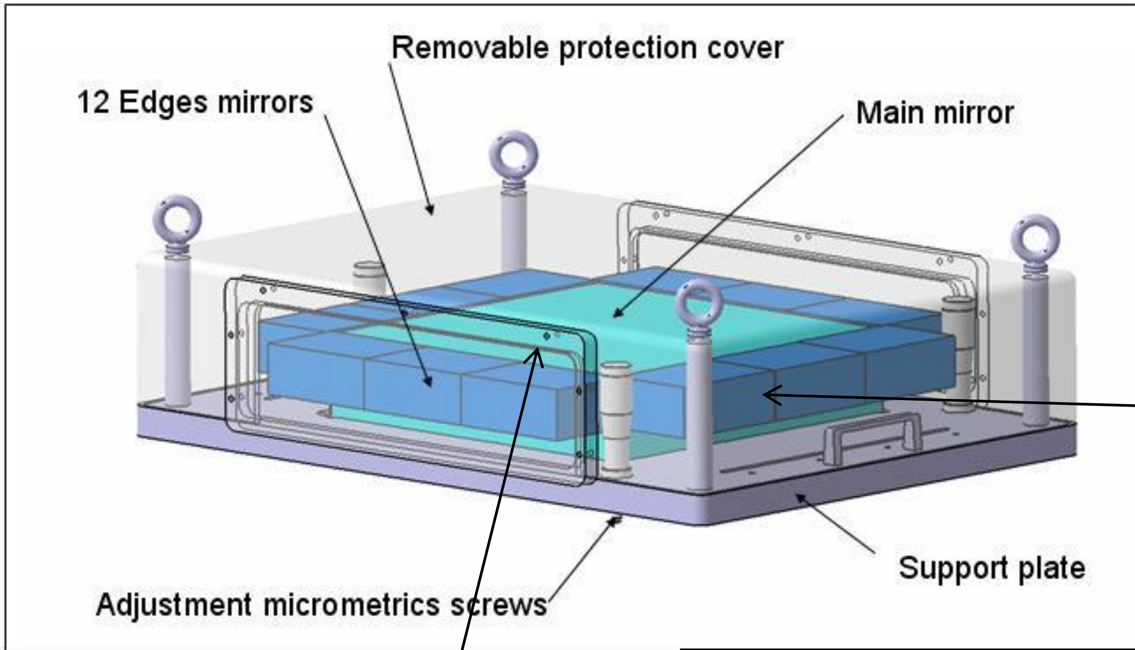
Storage of UCN in gravitational quantum states

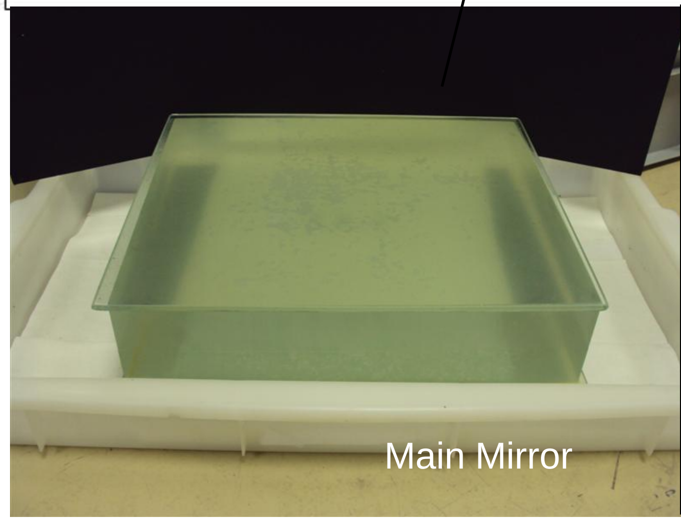


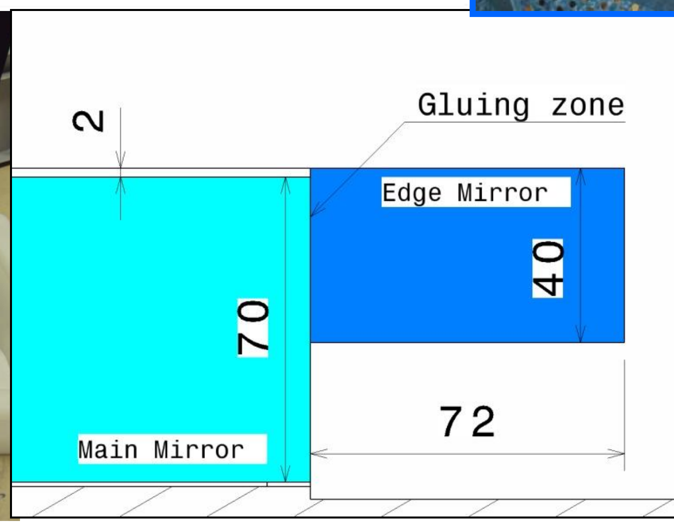


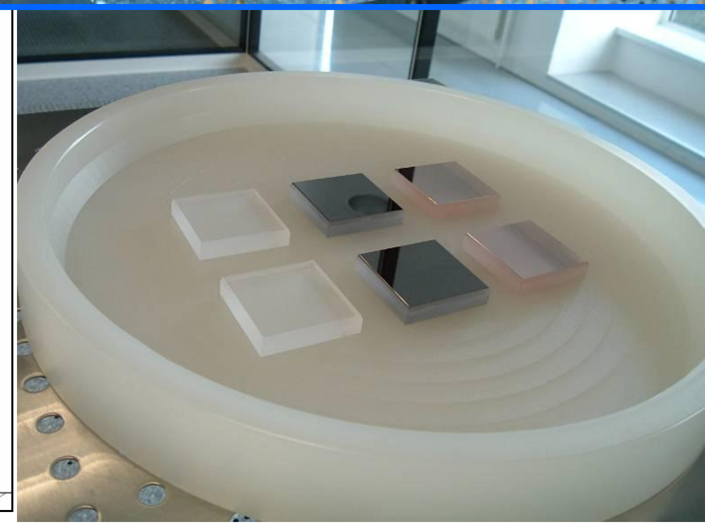


Transitions between gravitational quantum states
Quantum trap 30cm by 30cm; Height of edges 0.5mm

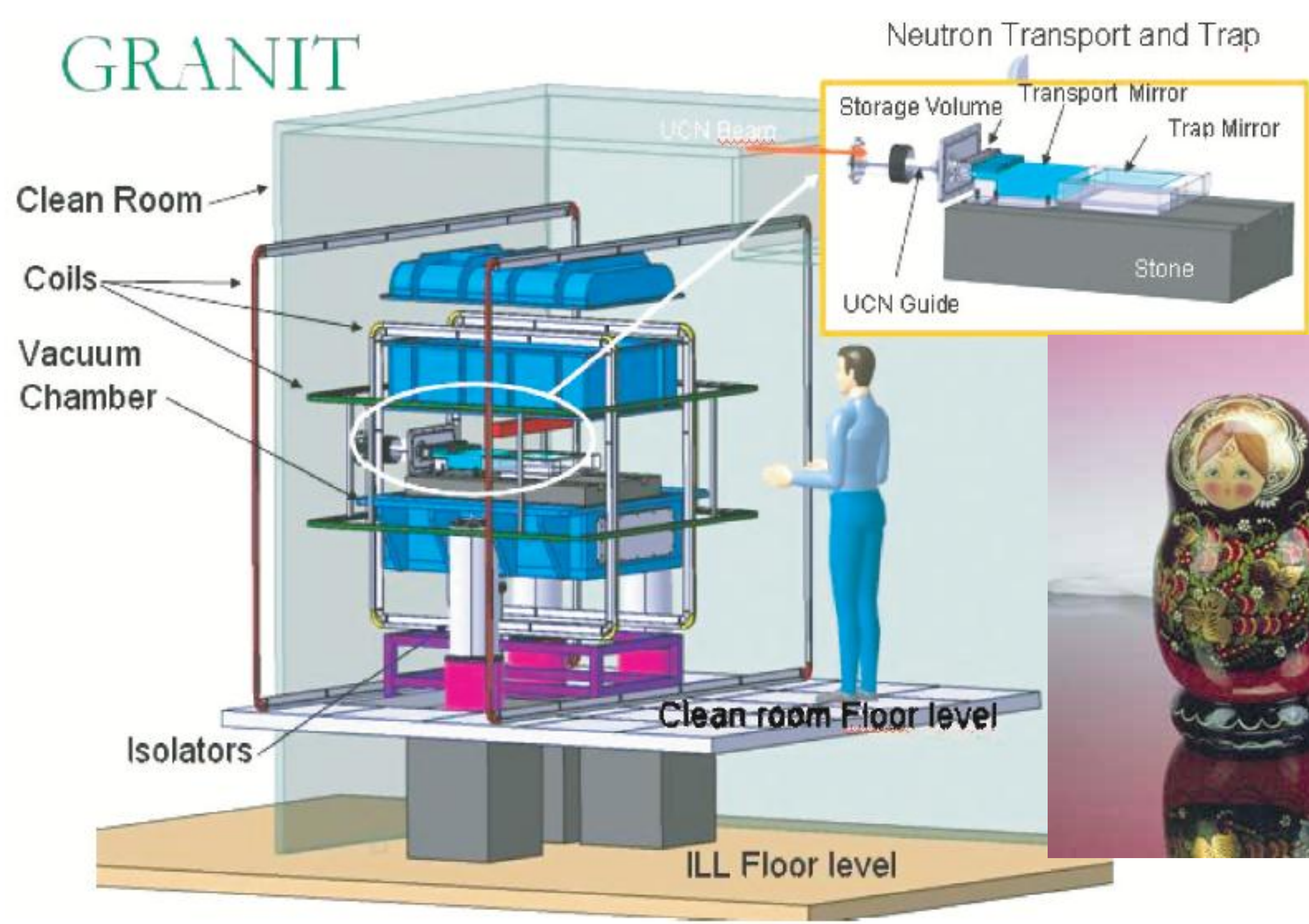


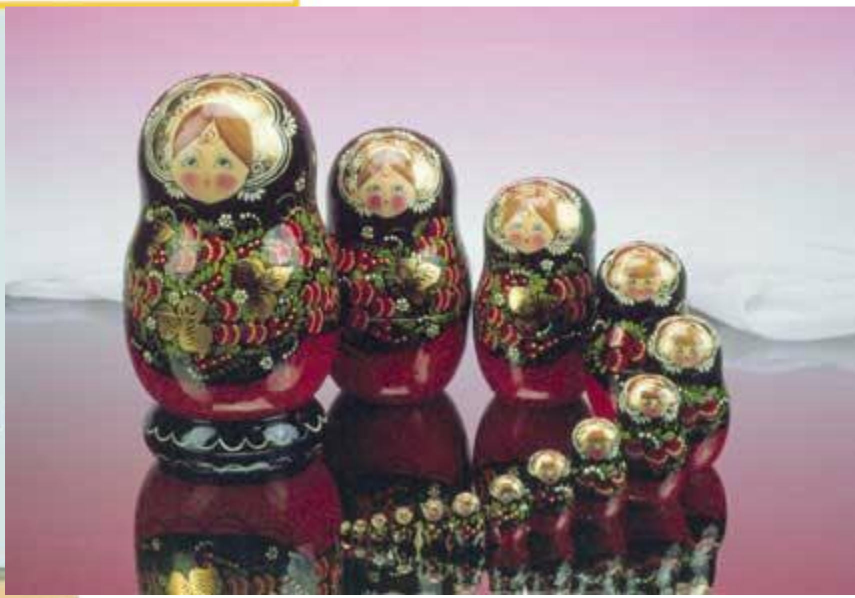




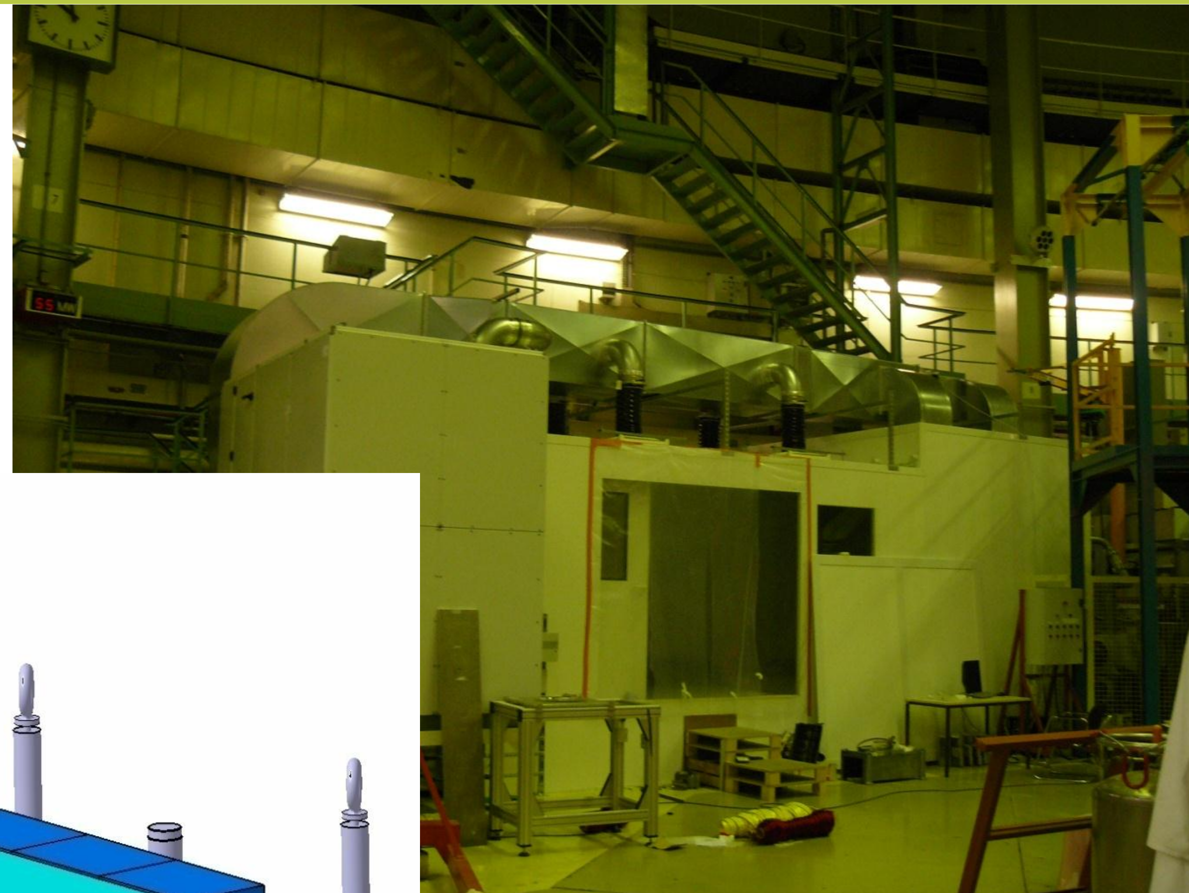


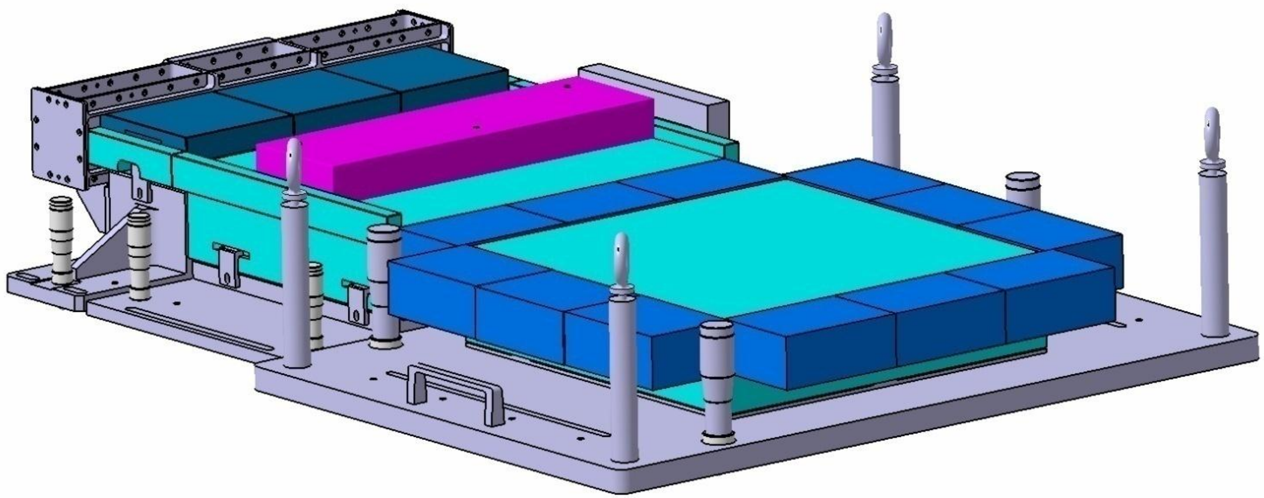
GRANIT
Assembling the spectrometer



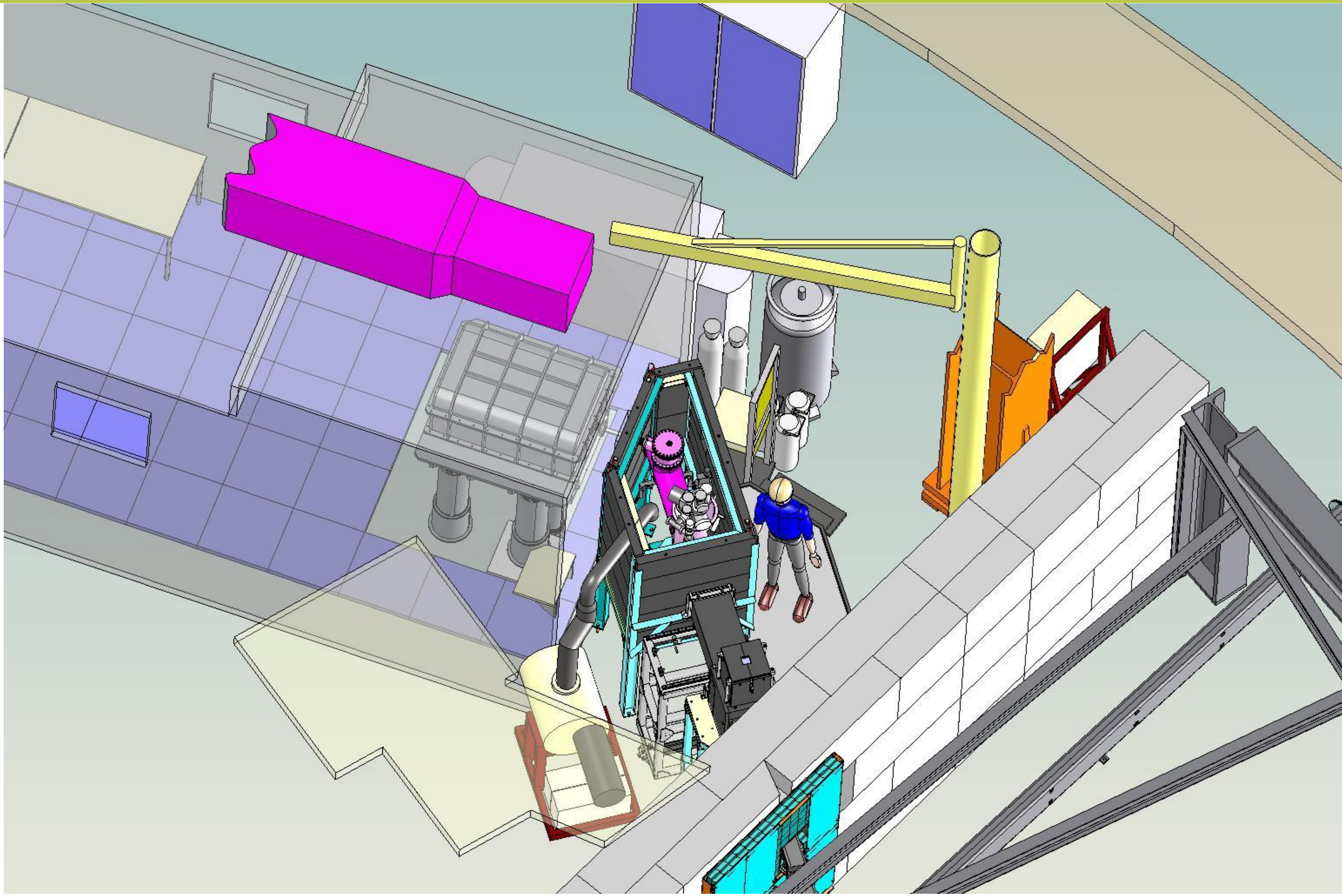


GRANIT
Extraction, transport, and storage mirrors; Clean room

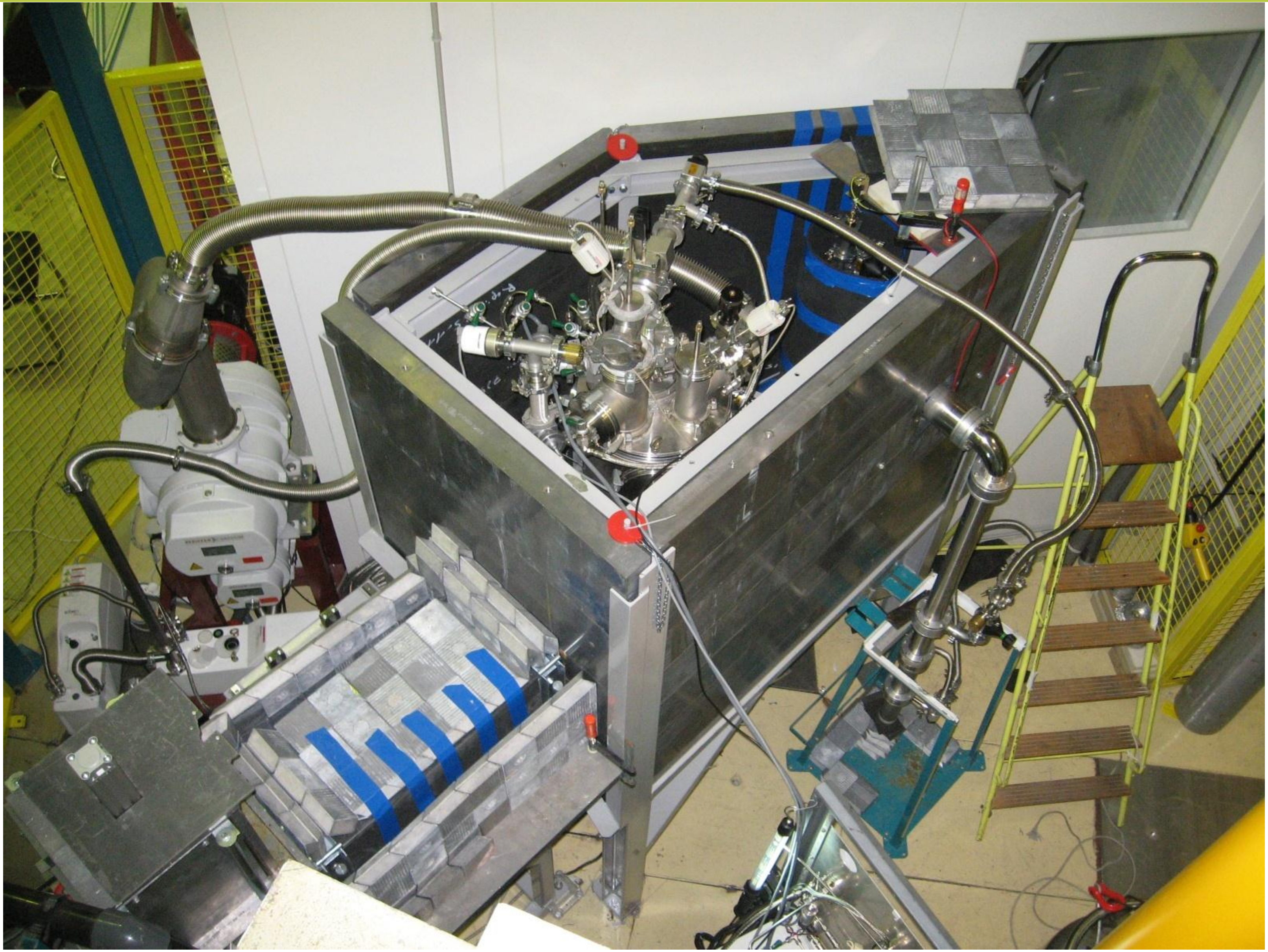




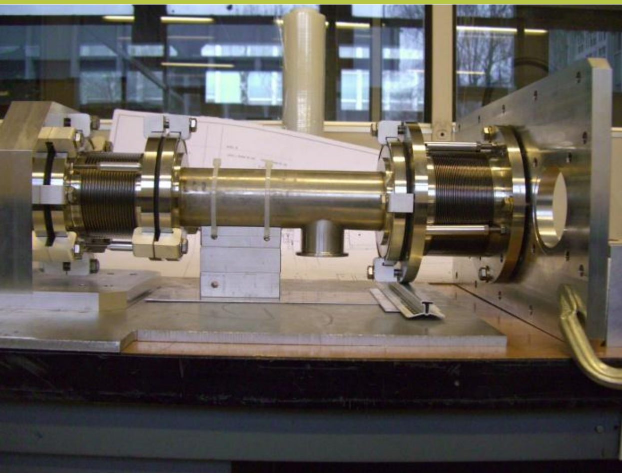
Installation of GRANIT spectrometer at the level C at ILL

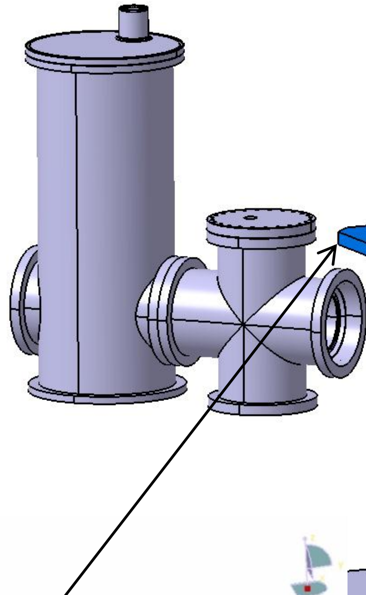


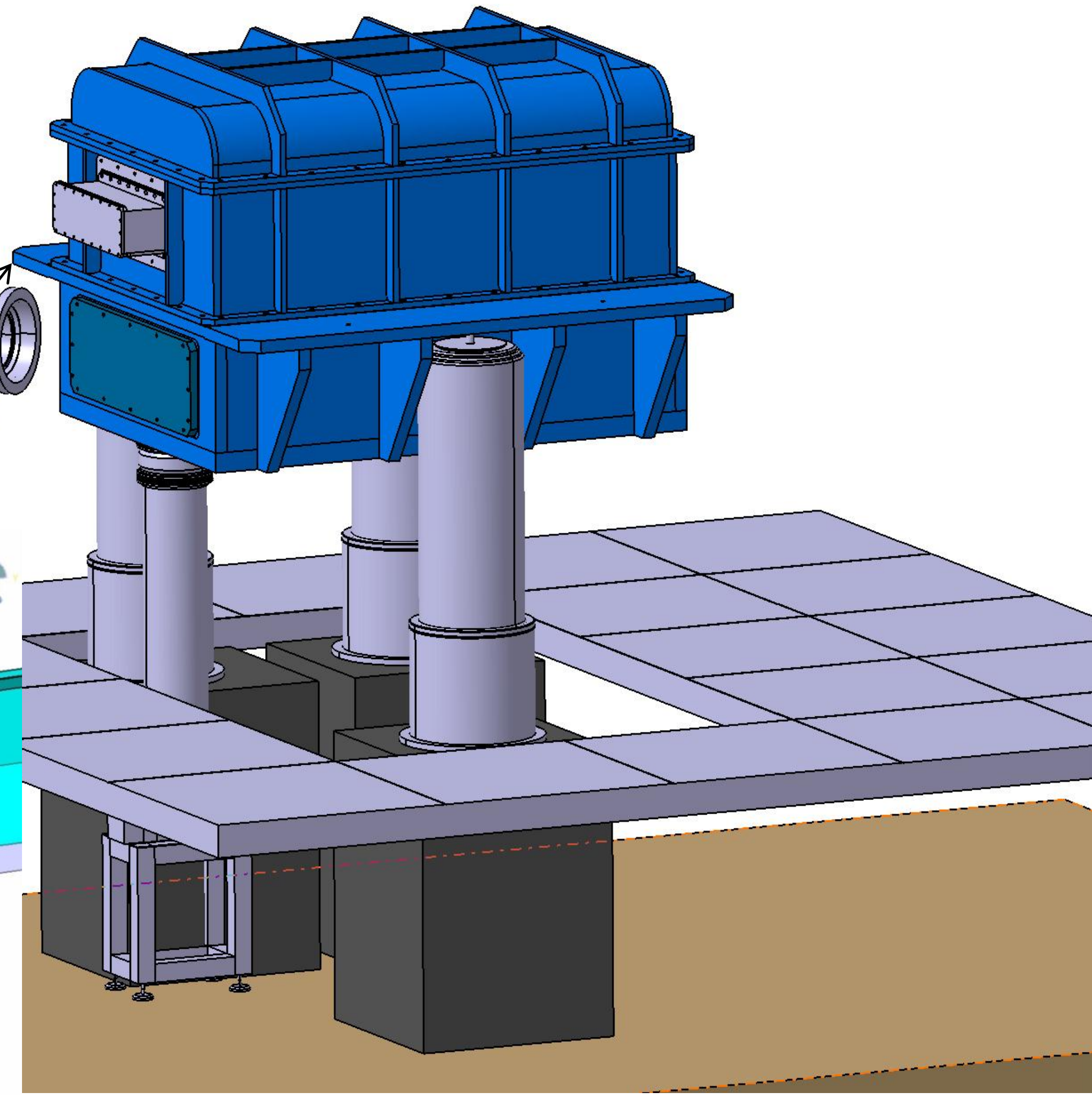
Installation of GRANIT spectrometer at the level C at ILL

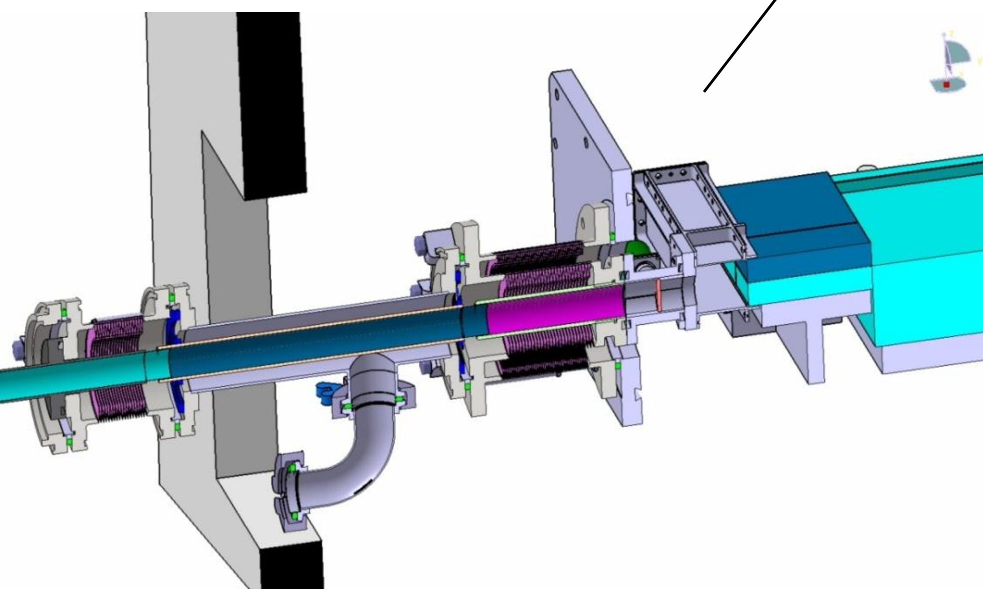


GRANIT and UCN source



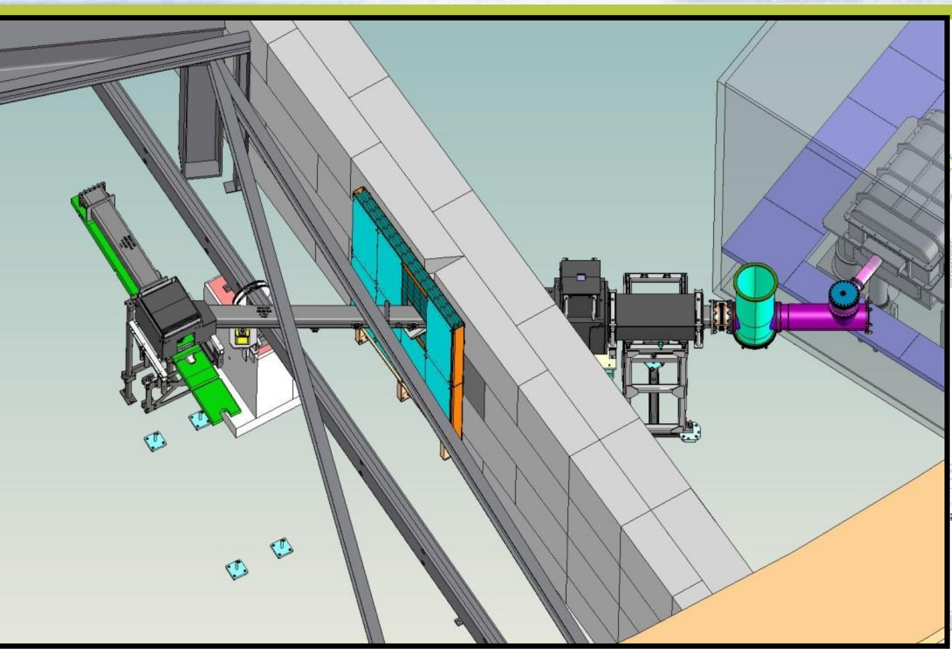


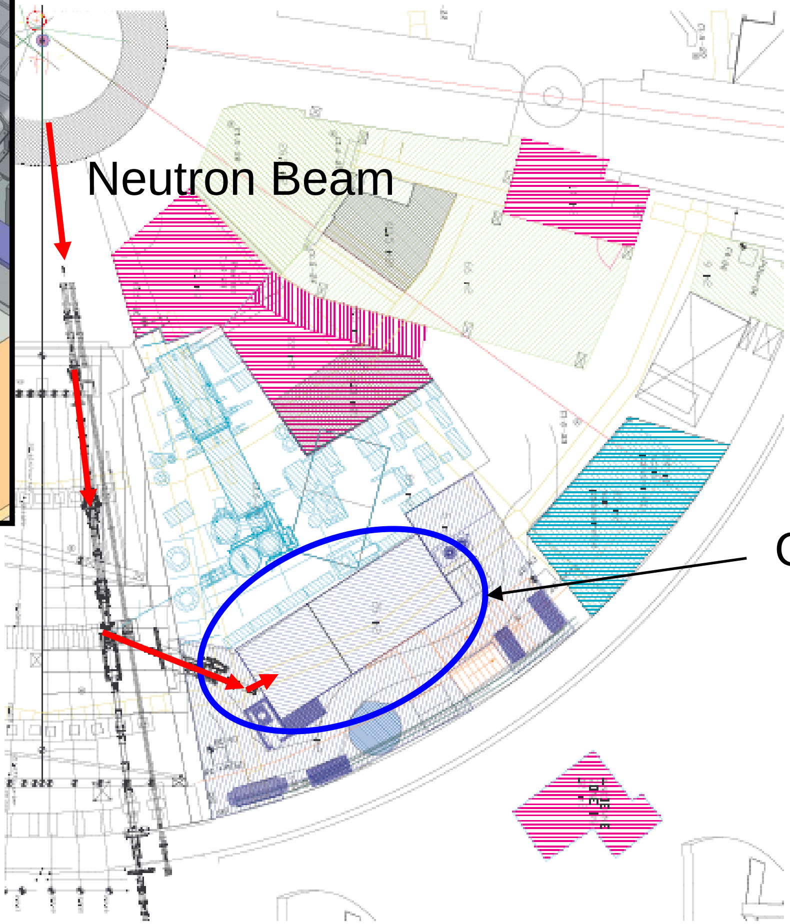




GRANIT
Control of magnetic fields, vacuum chamber

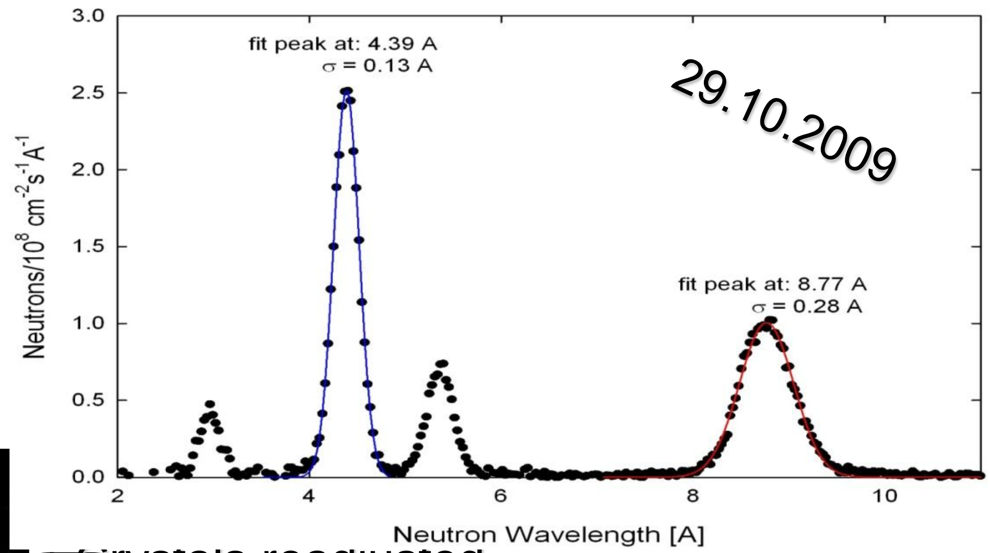
Installation of GRANIT spectrometer at the level C at ILL

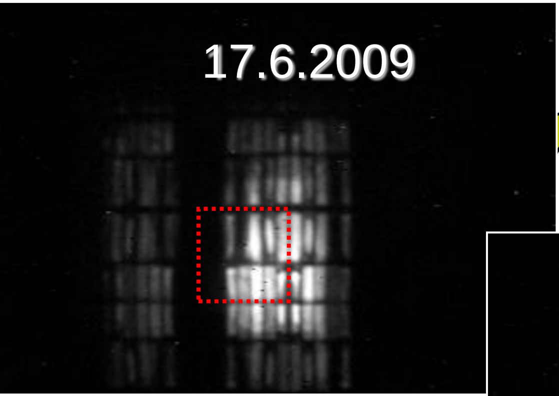




Located in the ILL reactor at level C

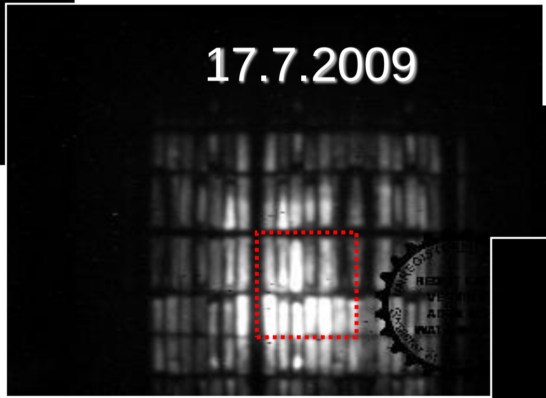
Installation of GRANIT spectrometer at the level C at ILL





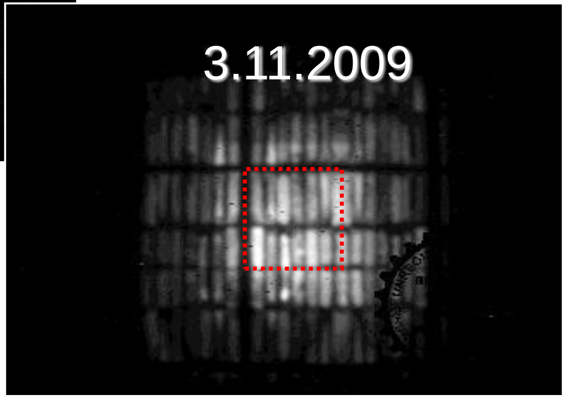
3.1×10^8 n $cm^{-2}s^{-1}$

Monochromator turned



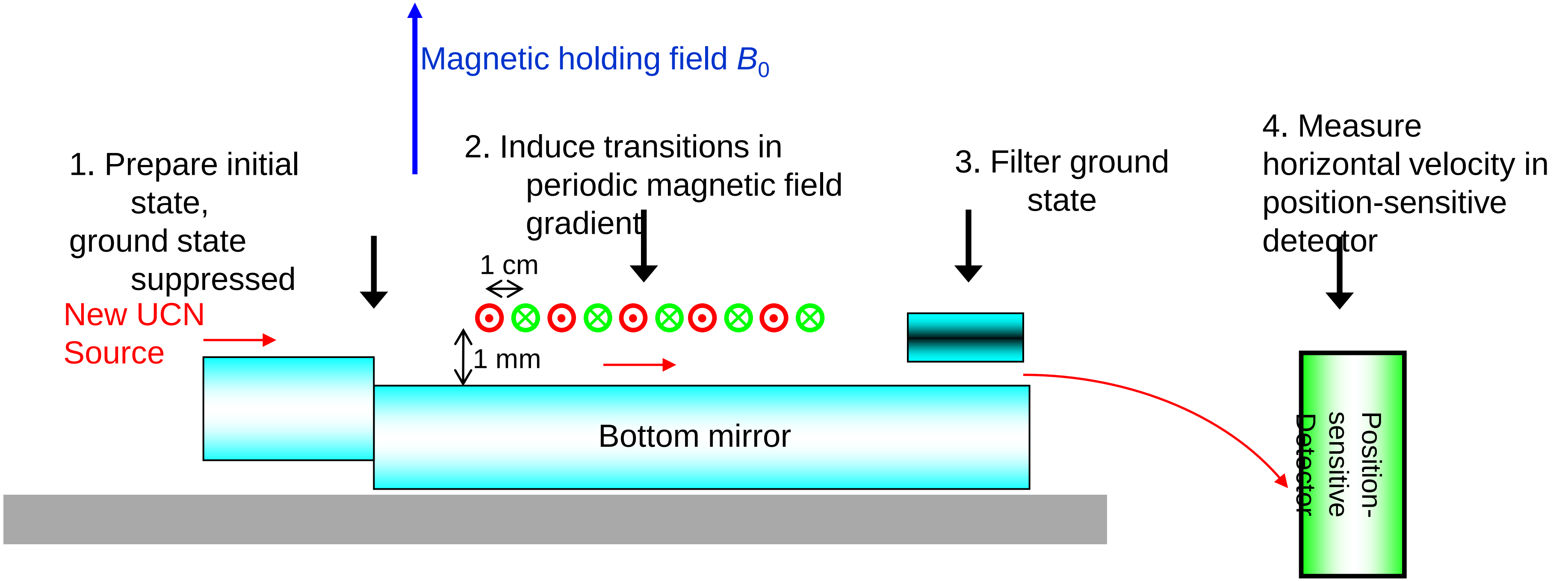
5.9×10^8 n $cm^{-2}s^{-1}$

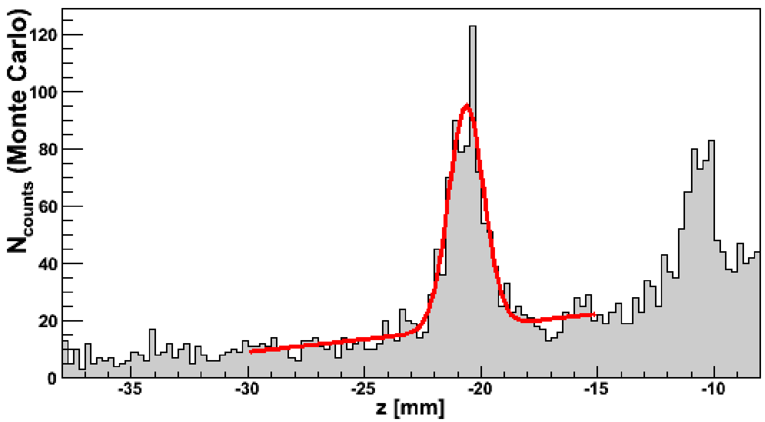
Crystals readjusted

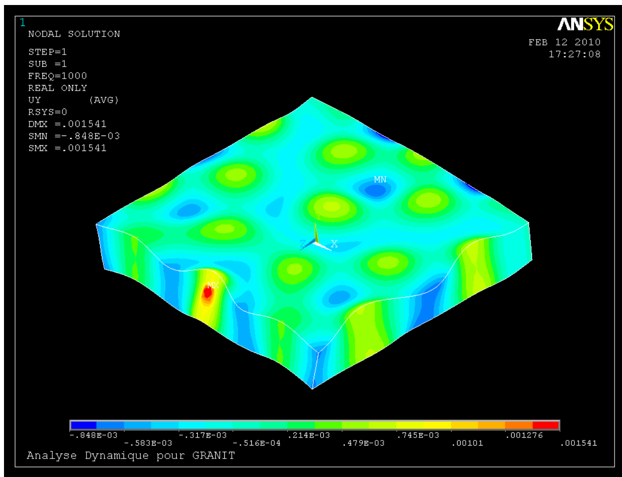


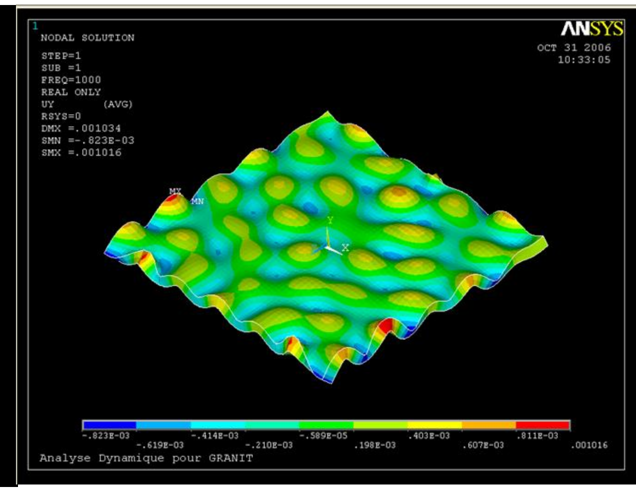
7.2×10^8 n $cm^{-2}s^{-1}$

GRANIT
on methods of excitation the transitions







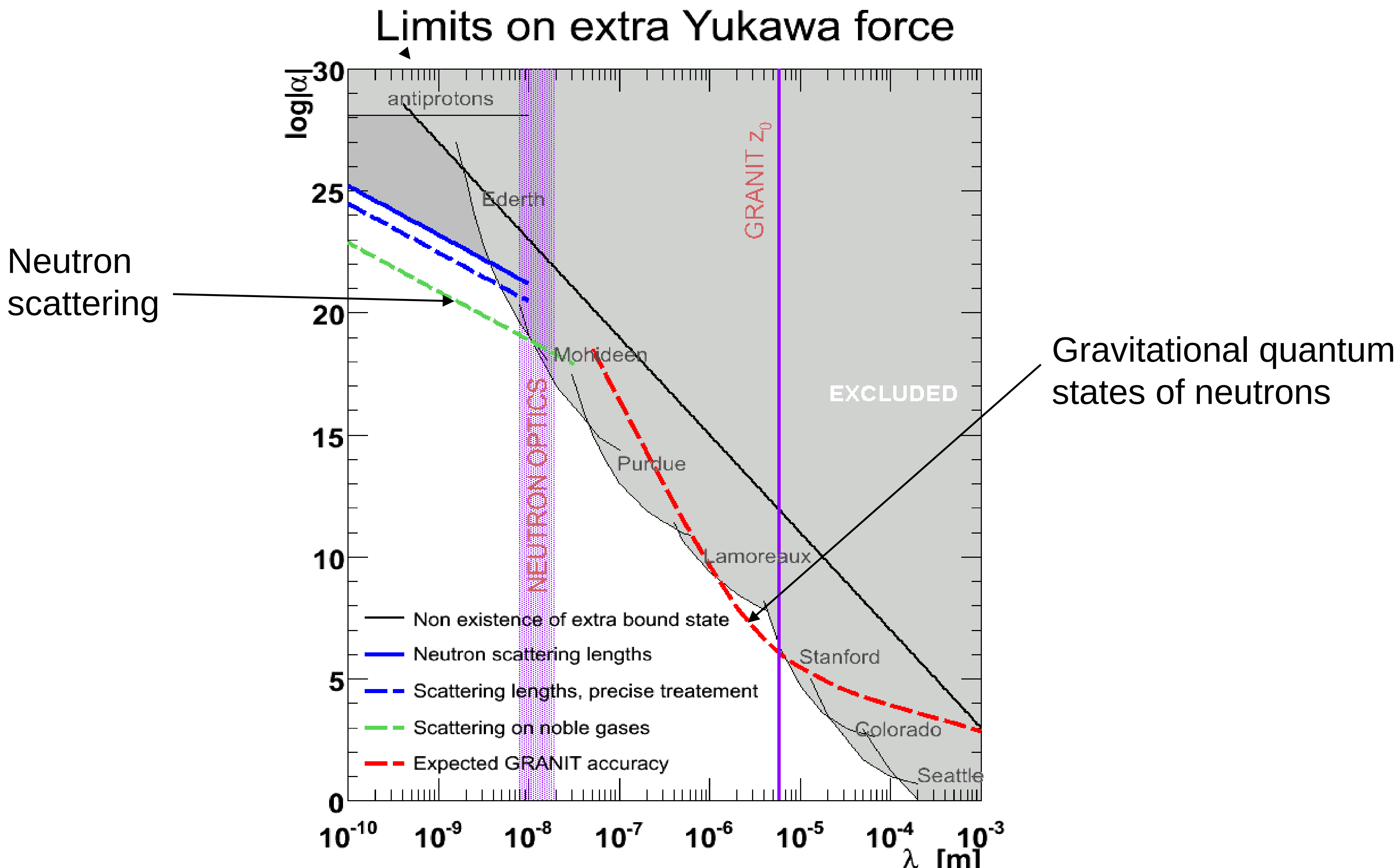


Applications

The phenomenon of gravitational quantum states of neutrons could be used in various applications, as apriory it provides a very « clean » system with well-defined quantum states.

-***Contraints for short-range forces;***
-***Constrains for axion-like forces;***
-***Constrains for neutron electric charge;***
-***Neutron quantum optics;***
-***UCN reflectometry;***
-***Quantum revivals;***
-***Constrains for logarithmic term in Schrödinger equation;***
-***Loss of quantum coherence;***
-***UCN extraction, transport, tight valves;***
-Study of thin surface layers;
-***etc....***

Constrains for short-range forces



V.V. Nesvizhevsky

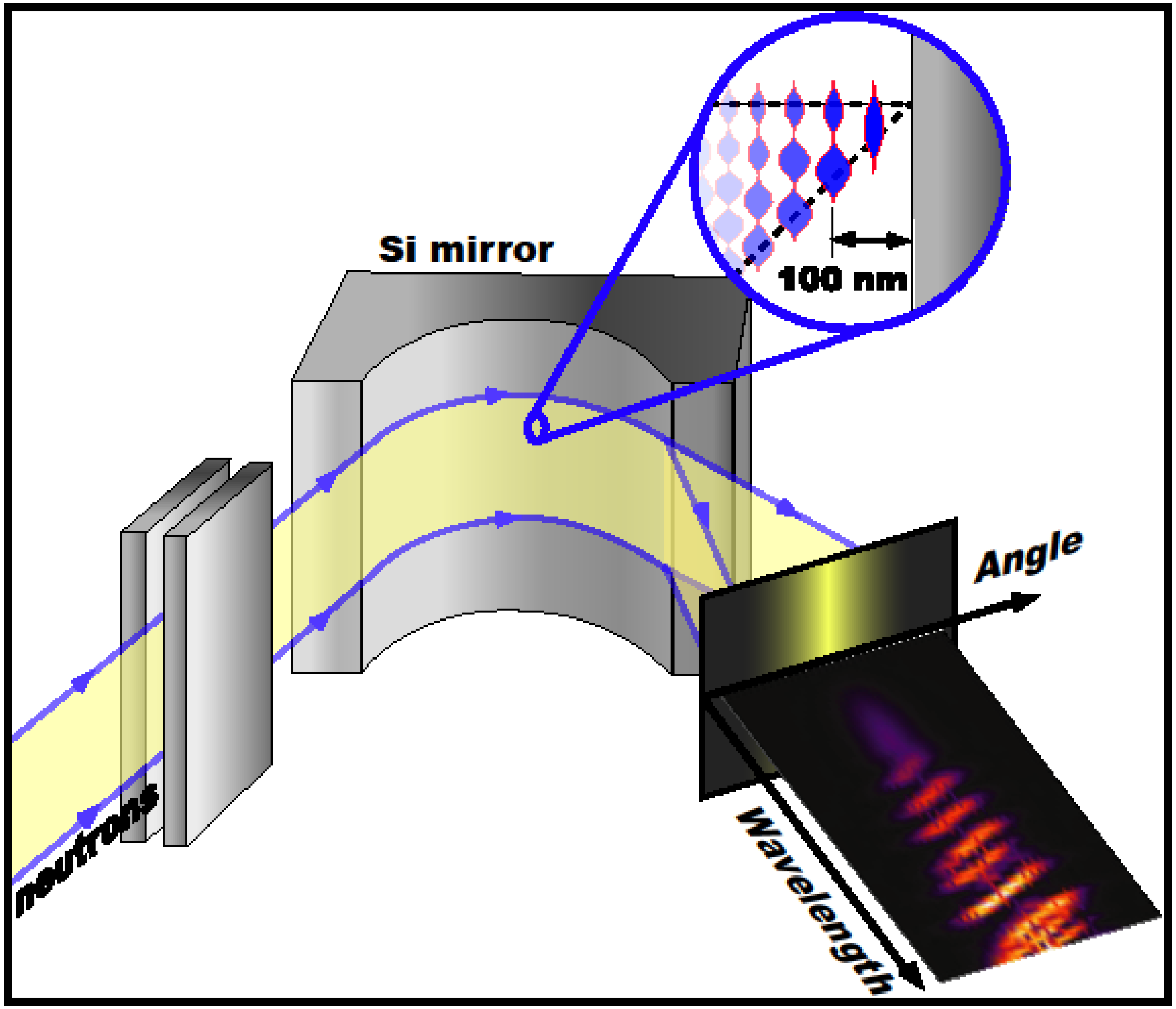
Conclusion (on gravitational quantum states)

NEUTRONS FOR SCIENCE

1. First observation of quantum states of ultracold neutrons in gravitational field above mirror
2. First direct demonstration (and still the only one!) of quantum states of matter in gravitational field
3. Applications of this phenomenon in fundamental and applied physics
4. New gravitational spectrometer GRANIT, with all parameters improved by many orders of magnitude compared to the first setup, is going to become operational this year

Neutron whispering gallery

R. Cubitt, V.V. Nesvizhevsky, K.V. Protasov, A.Yu. Voronin



Neutron whispering gallery

nature physics

LETTERS

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***Nature Physics*, 6,** *114-117 (2010)*

Neutron whispering gallery

Valery V. Nesvizhevsky[1]*, Alexei Yu. Voronin[2], Robert Cubitt[1] and Konstantin V. Protasov[3]

The 'whispering gallery' effect has been known since ancient times for sound waves in air[1,2], later in water and more recently for a broad range of electromagnetic waves: radio, optics, Roentgen and so on[3–6]. It consists of wave localization near a curved reflecting surface and is expected for waves of various natures, for instance, for atoms[7,8] and neutrons[9]. For matter waves, it would include a new feature: a massive particle would be settled in quantum states, with parameters depending on its mass. Here, we present for the first time the quantum whispering-gallery effect for cold neutrons. This phenomenon provides an example of an exactly solvable problem analogous to the 'quantum bouncer'[10]; it is complementary to the recently discovered gravitationally bound quantum states of neutrons[11]. These two phenomena provide a direct demonstration of the weak equivalence principle for a massive particle in a pure quantum state[12]. Deeply bound whispering-gallery states are long-living and weakly sensitive to surface potential; highly excited states are short-living and very sensitive to the wall potential shape. Therefore, they are a promising tool for studying fundamental neutron–matter interactions[13–15], quantum neutron optics and surface physics effects[16–18].

The classical whispering-gallery phenomenon can be understood

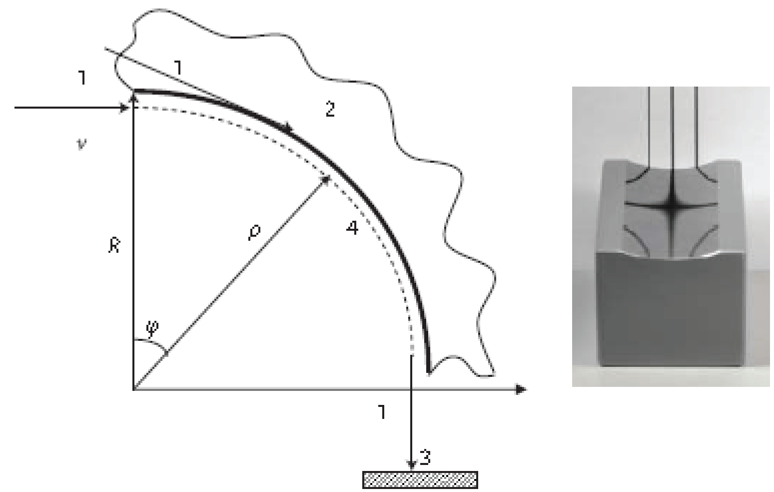
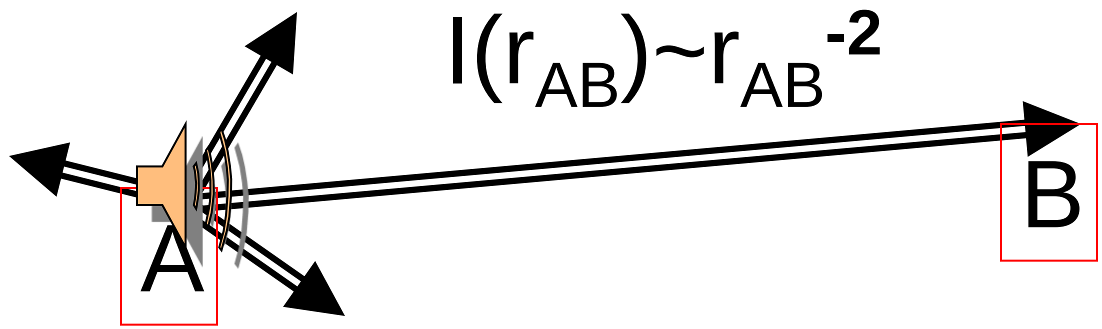


Figure 1 | A scheme of the neutron centrifugal experiment. 1: Classical trajectories of incoming and outgoing neutrons, 2: cylindrical mirror, 3: neutron detector, 4: quantum motion along the mirror surface. Inset: A photo of the single-crystal cylindrical silicon mirror used for the presented experiments, with an optical reflection of black stripes for illustrative purposes.

Neutron whispering gallery

Propagation of sound (or other) wave in loss-free medium in 3-D space without boundaries



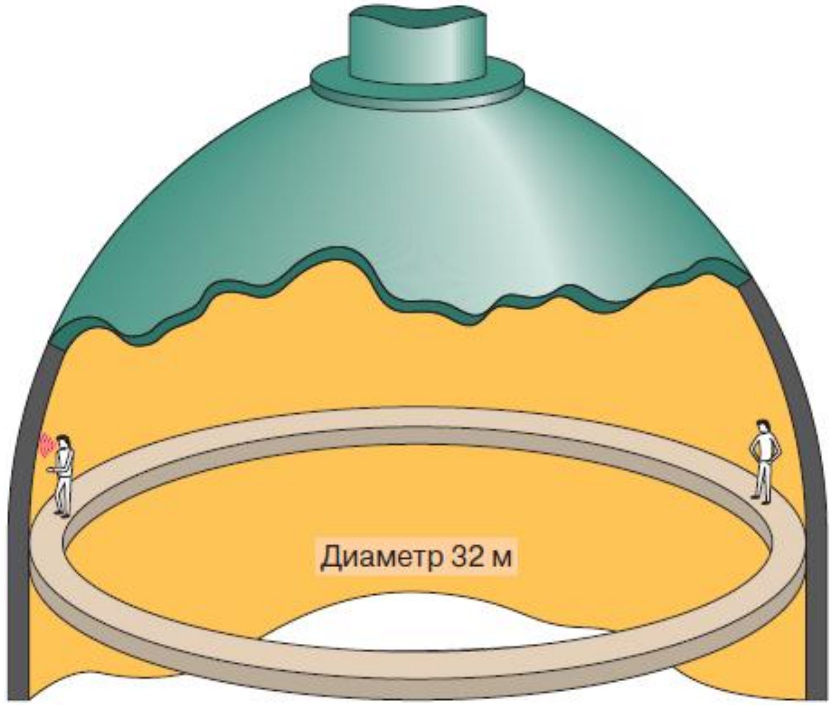
Any wave

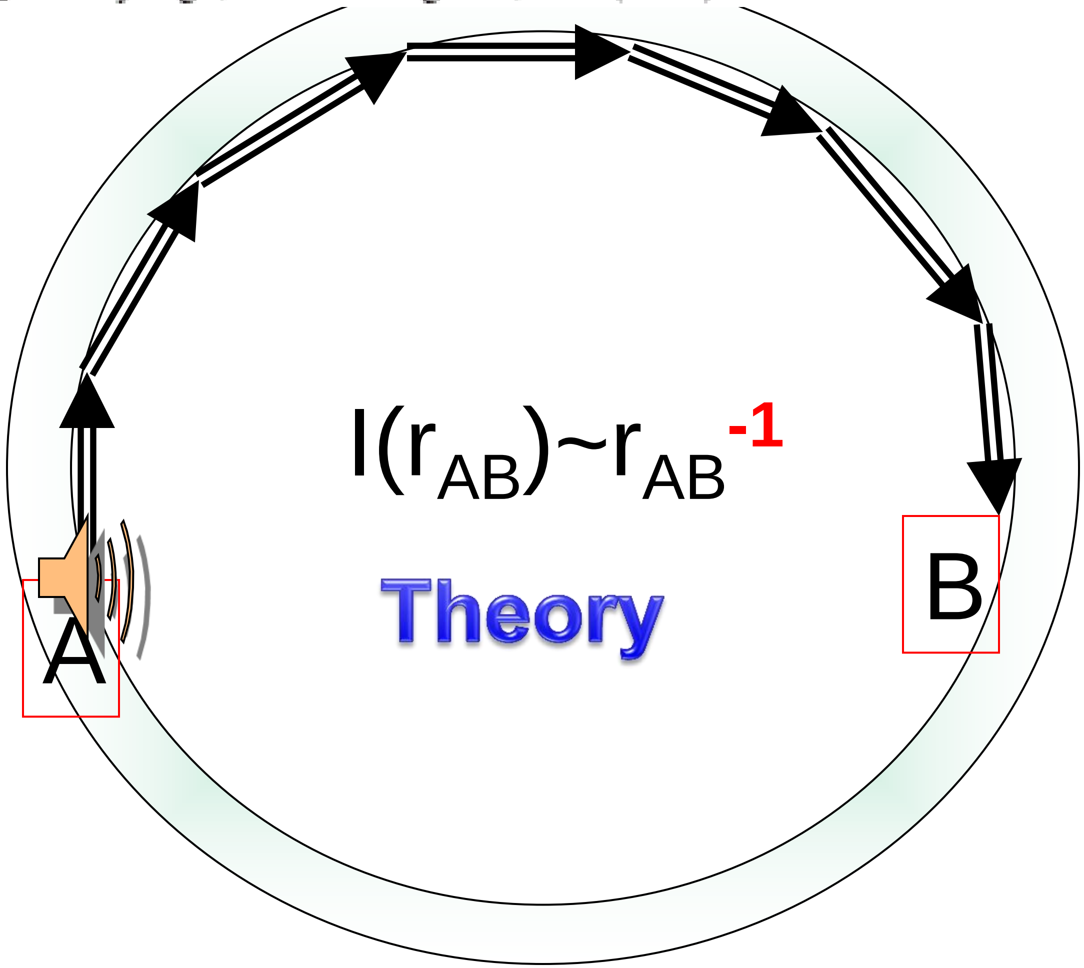
Neutron whispering gallery

Known phenomenon of “Whispering Gallery”:

[1] J. W. Strutt Baron Rayleigh, *The Theory of Sound* (Macmillan, London 1878), Vol. 2.
[2] L. Rayleigh, Philos. Mag. 27, 100 (1914).

Proragation of sound in closed building (distance r_{AB} is measured along surface)





Neutron whispering gallery

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Known phenomenon of "Whispering Gallery":

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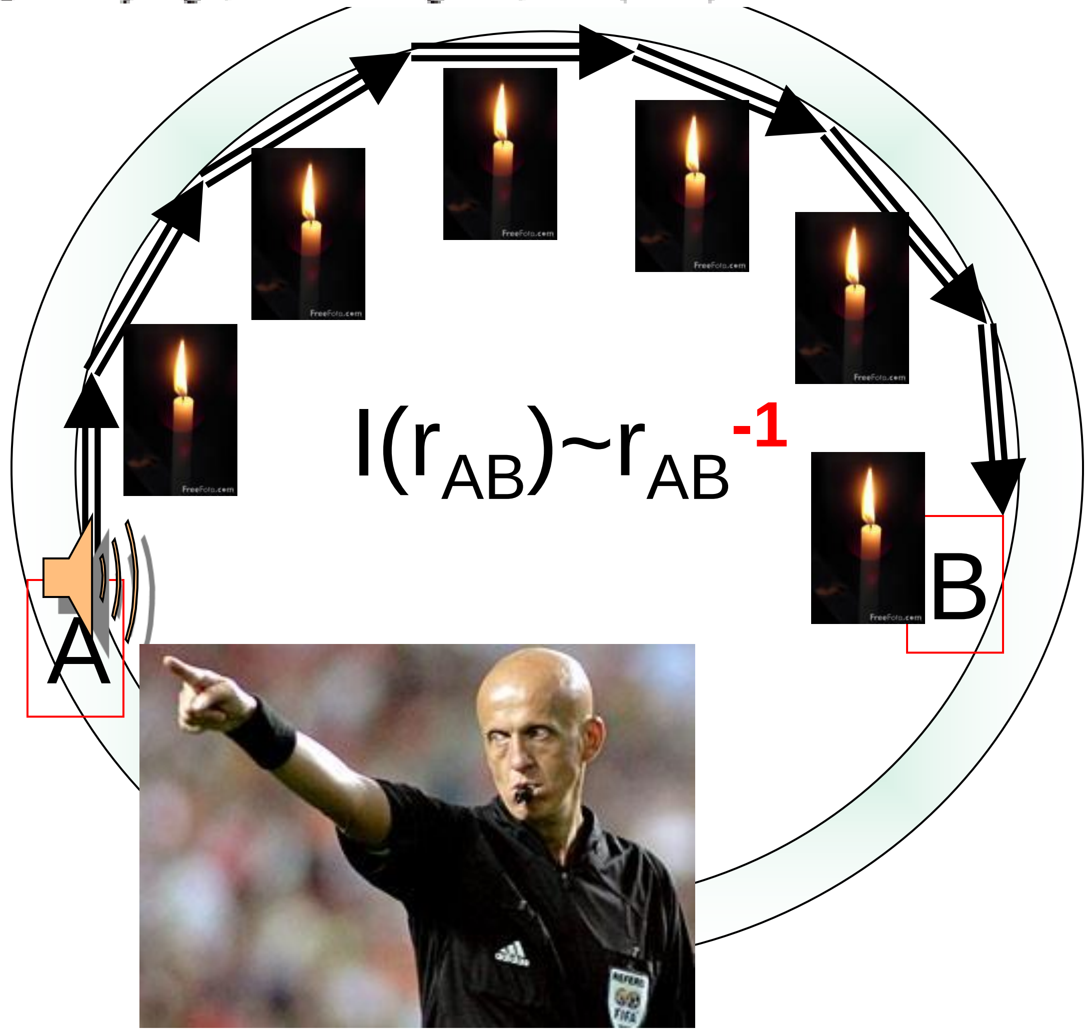

Experiment

Neutron whispering gallery

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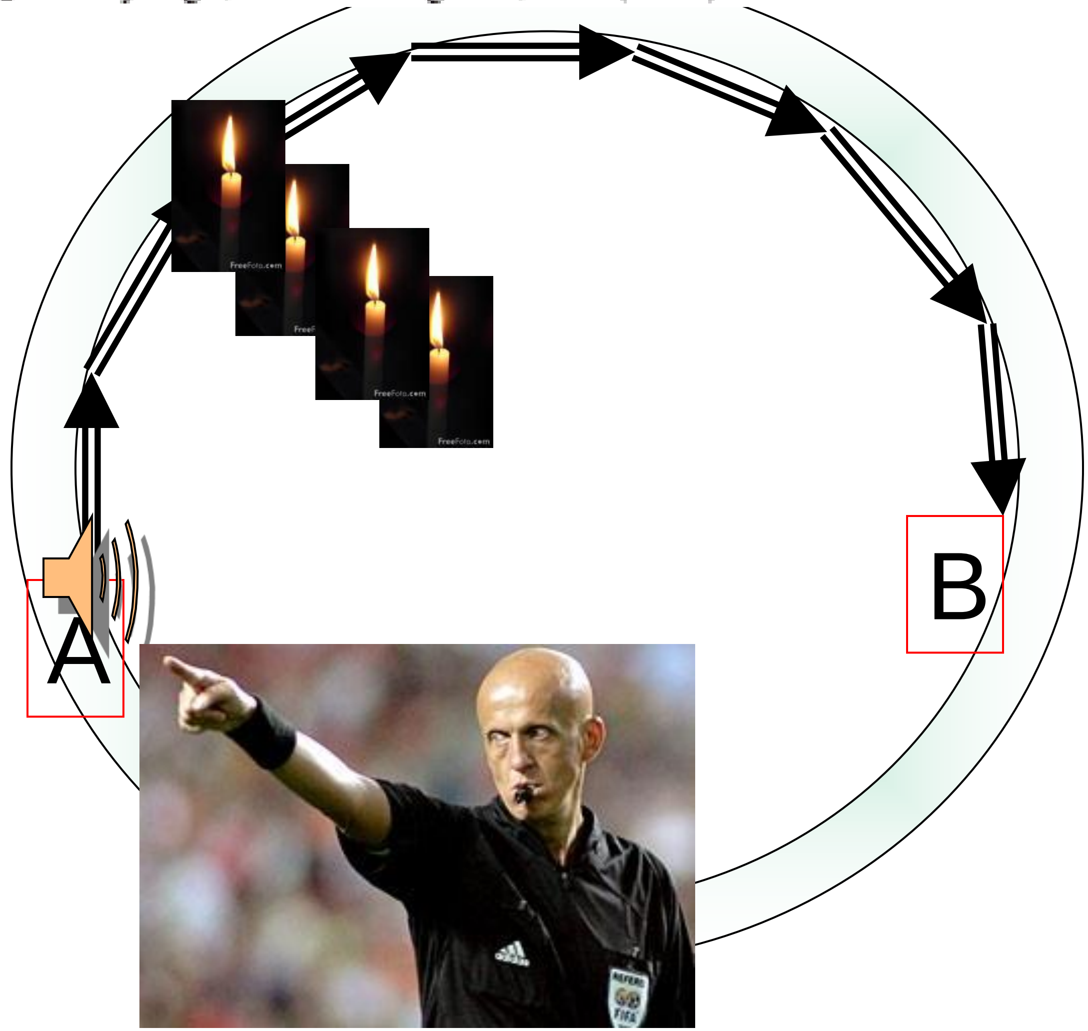

Experiment

Neutron whispering gallery



Whales are supposed to communicate at huge distances using analogous effect in surface ocean water layers (due to gradient of salt concentration, thus due to gradient of refractive index).

Other examples

Analogous phenomena are observed and used in optics, for radio-, Roentgen waves ...

Radio: Debye, P. Der lichtdruck auf kugeln von beleibigem material. *Ann. Physik* **30**, 57-136 (1909).

In optics, for example: to stabilize laser frequency, for non-linear signal transformation

[3] A. N. Oraevsky, Quantum Electron. 32, 377 (2002).

[4] K. J. Vahala, Nature (London) 424, 839 (2003).

Neutron whispering gallery / proposal

PHYSICAL REVIEW A 78, 1 (2008)

Centrifugal quantum states of neutrons

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(Received 24 June 2008)

We propose a method for observation of the quasistationary states of neutrons localized near a curved mirror surface. The bounding effective well is formed by the centrifugal potential and the mirror Fermi potential. This phenomenon is an example of an exactly solvable "quantum bouncer" problem that can be studied experimentally. It could provide a promising tool for studying fundamental neutron-matter interactions, as well as quantum neutron optics and surface physics effects. We develop a formalism that describes quantitatively the neutron motion near the mirror surface. The effects of mirror roughness are taken into account.

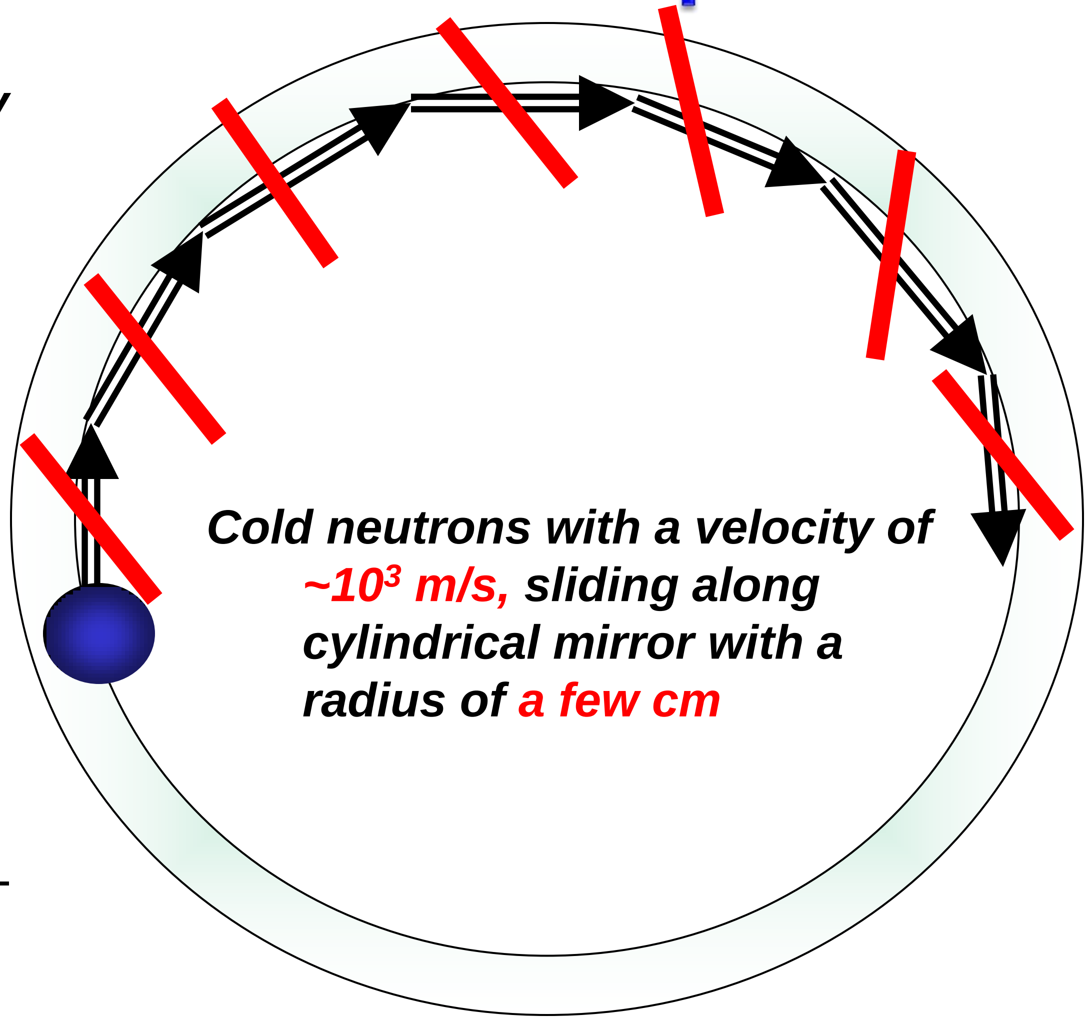
Neutron whispering gallery

Massive particle, ***sliding along curved mirror surface is settled, under certain conditions, in quasi-stationarry quantum states***

Such a phenomenon has been considered (but not yet observed) for ultracold atoms:

- Mabuchi H. & Kimble H.J. Atom galleries for whispering atoms – binding atoms in stable orbits around an optical resonator. *Opt. Lett*. **19**, 749-751 (1994).
- Vernooy D. M. & Kimble H.J. Quantum structure and dynamics for atom galleries. *Phys. Rev. A* **55**, 1239-1261 (1997).

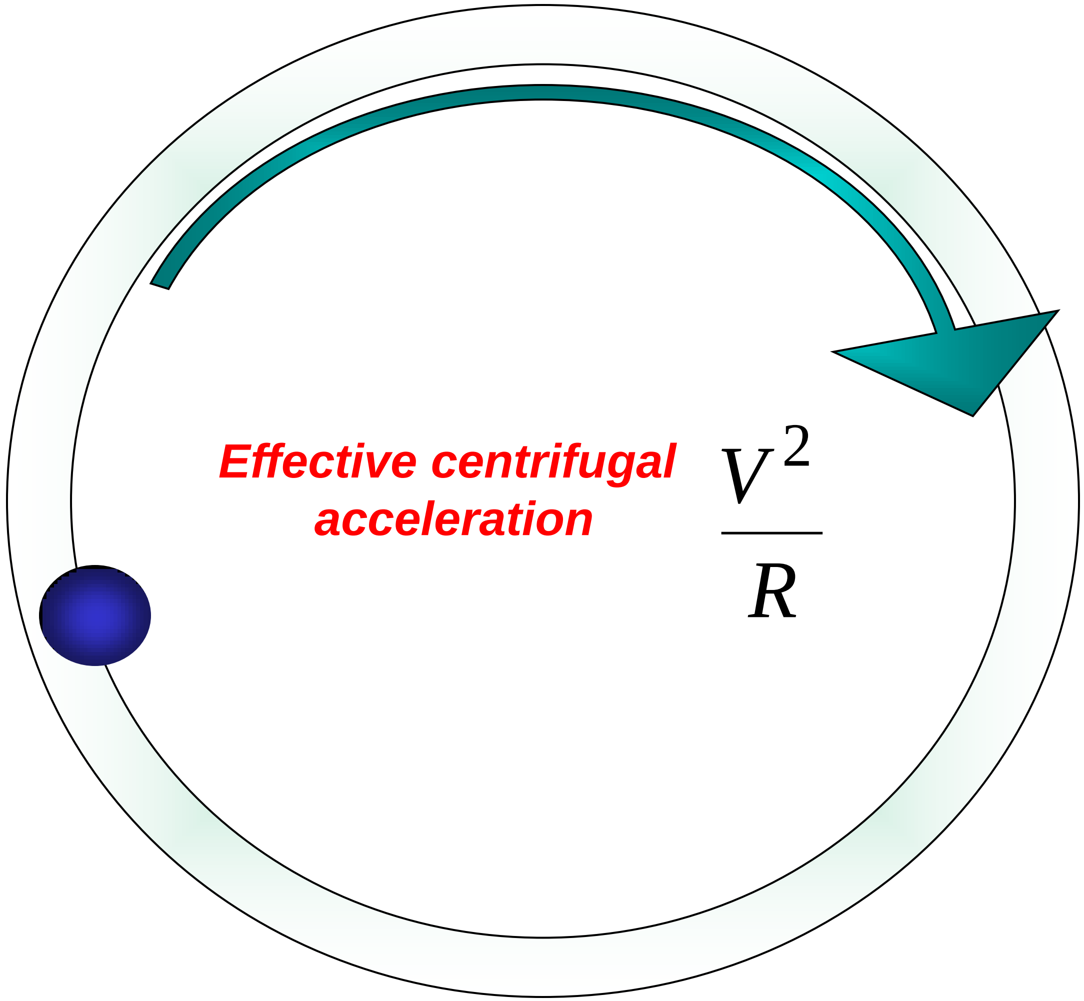
Characteristic parameters



Cold neutrons with a velocity of ~10^3 m/s, sliding along cylindrical mirror with a radius of a few cm

Two velocity components

If the characteristic size of quantum states and quasi-classical distance between two collisions are much smaller than the mirror radius then ***tangential and longitudal motions could be separated***



Neutron whispering gallery

$$-\frac{\hbar^2}{2m}\frac{d^2}{dz^2}\psi + m\frac{v^2}{R}z\,\psi = E\,\psi \qquad \text{outside the mirror}$$

$$-\frac{\hbar^2}{2m}\frac{d^2}{dz^2}\psi + \left(m\frac{v^2}{R}z + V_F\right)\psi = E\,\psi \qquad \text{inside the mirror}$$

$$V_F \sim 10^{-7}\,eV$$

Radial motion of neutrons (axis z) close to mirror surface is described using this Schrödinger equation

Precise solution

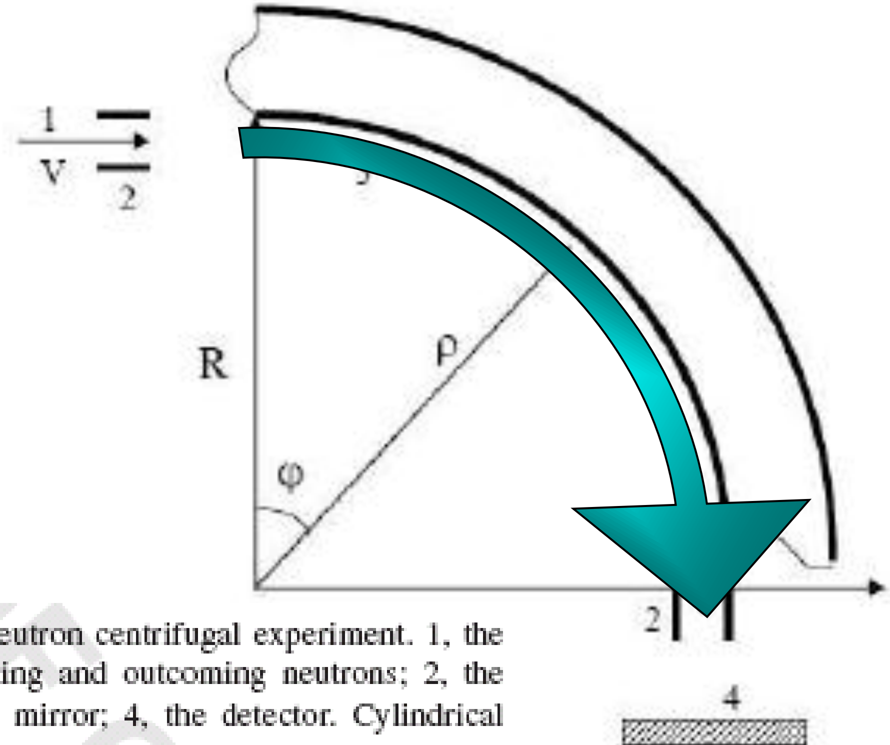
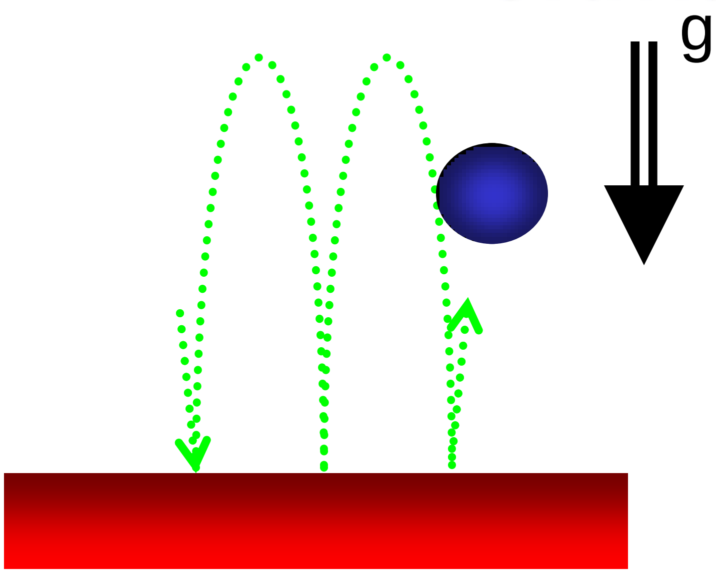
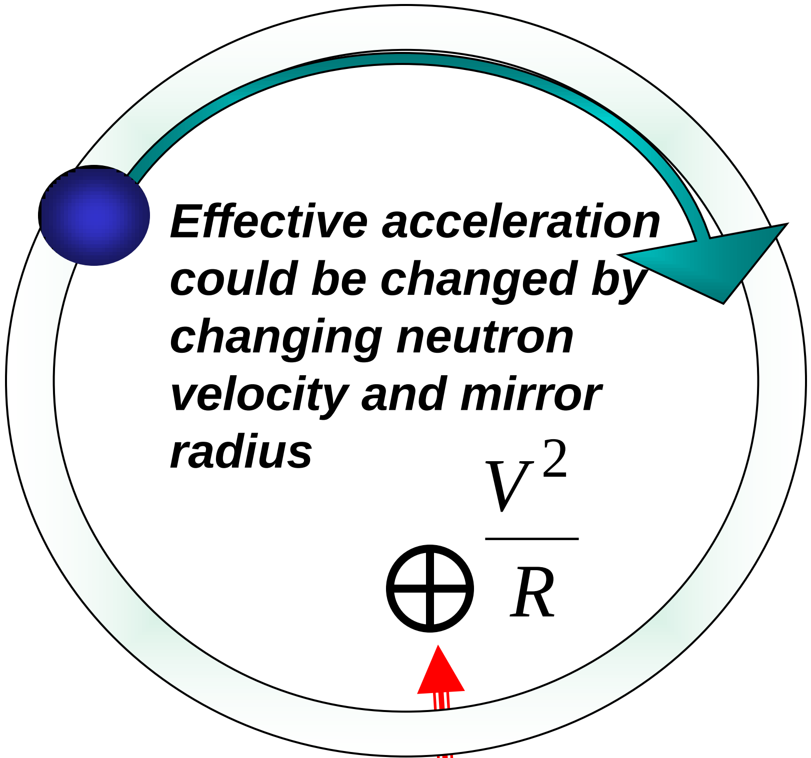


FIG. 1. A scheme of the neutron centrifugal experiment. 1, the classical trajectories of incoming and outcoming neutrons; 2, the collimators; 3, the cylindrical mirror; 4, the detector. Cylindrical coordinates $\rho-\varphi$ used throughout the paper are shown.

Gravity / Acceleration



Neutron above mirror in gravity field



Energy of quantum states in Bohr-Zommerfeld approximation :

$$E_n \approx \sqrt[3]{\left(\frac{9 \cdot m_n}{8}\right) \cdot \left(\pi \cdot \hbar \cdot g \cdot \left(n - \frac{1}{4}\right)\right)^2}$$

Comparison to gravitational quantum states of neutrons

Gravity / Acceleration

$$E_n \approx \sqrt[3]{\left(\frac{9 \cdot m_n}{8}\right) \cdot \left(\pi \cdot \hbar \cdot g \cdot \left(n - \frac{1}{4}\right)\right)^2}$$

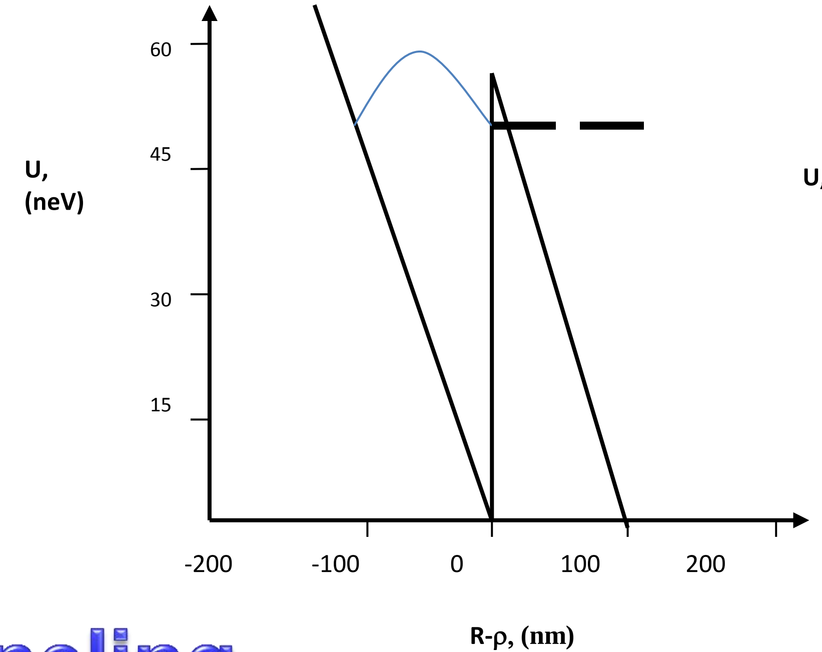
Illustration for quantum motion of an object above mirror in gravitational field and that in accelerating frame. Positions of the ball correspond to its most probable heights in 5th quantum state. The vertical scale corresponds to the neutron mass.

Methods of observation

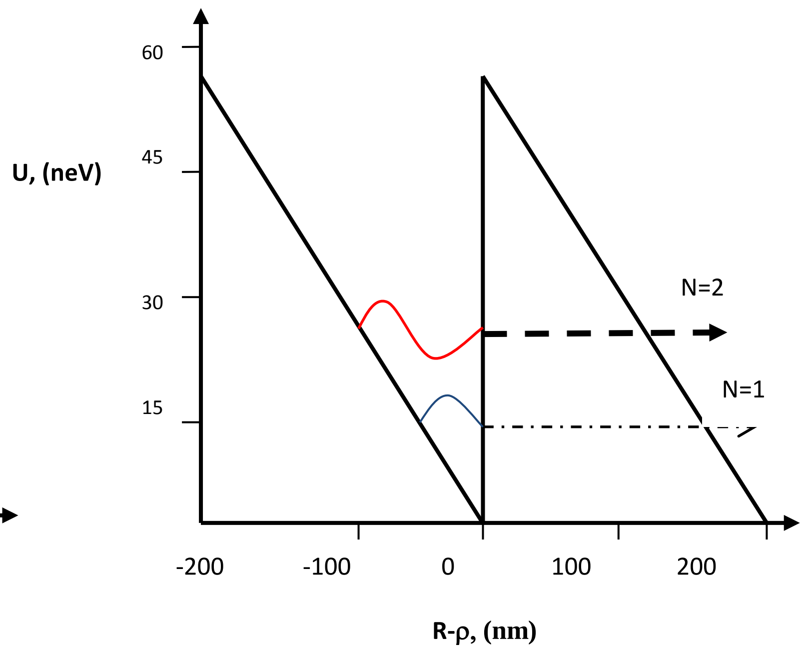
$$\Gamma_n = \left(\frac{\hbar^2 M v^4}{2R^2}\right)^{1/3} \frac{\sqrt{z_0 - \lambda_n}}{z_0} \exp\left[-\tfrac{4}{3}\left(z_0 - \lambda_n\right)^{3/2}\right]$$

$$\lambda_n = E_n / \left(\frac{\hbar^2 M v^4}{2R^2}\right)^{1/3} \qquad z_0 = V_F / \left(\frac{\hbar^2 M v^4}{2R^2}\right)^{1/3}$$

Life-times of quasi-stationary states due to tunneling as a function of energy



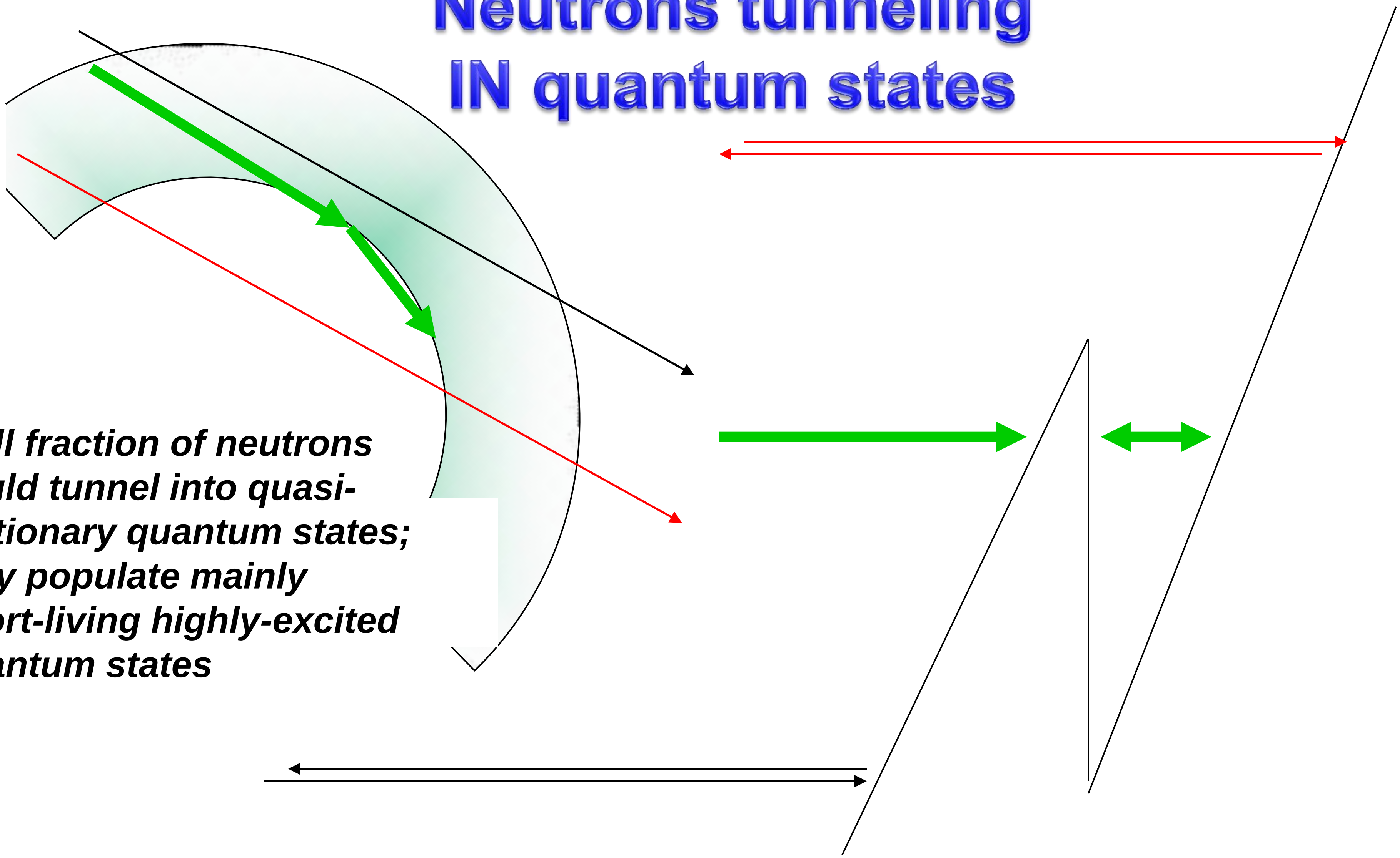
λc



λ>λc

Tunneling

Neutrons tunneling IN quantum states



A small fraction of neutrons could tunnel into quasi-stationary quantum states; they populate mainly short-living highly-excited quantum states

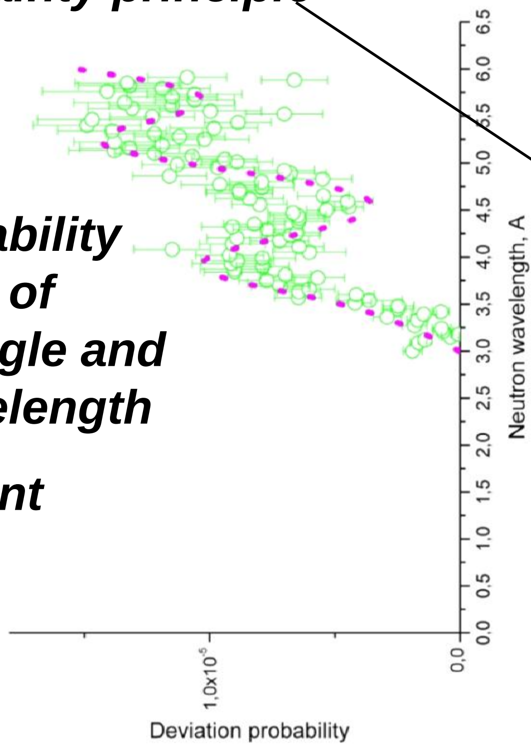
Neutrons tunneling IN quantum states

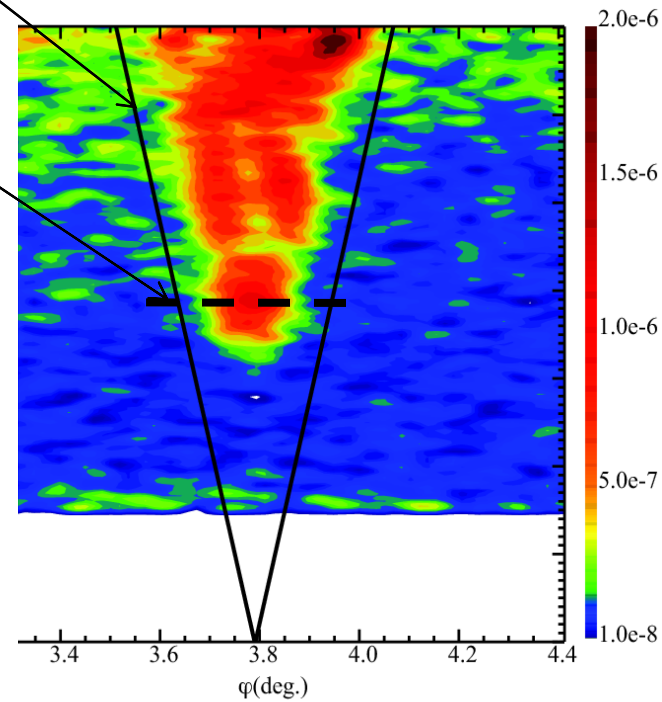
Solid lines define « classical » shape of the signal; horizontal line indicates estimation of the neutron wavelength resulting from the uncertainty principle

Scattering probability as a function of neutron wavelength (axis y) and scattering angle (axis x)

Scattering probability as a function of scattering angle and neutron wavelength

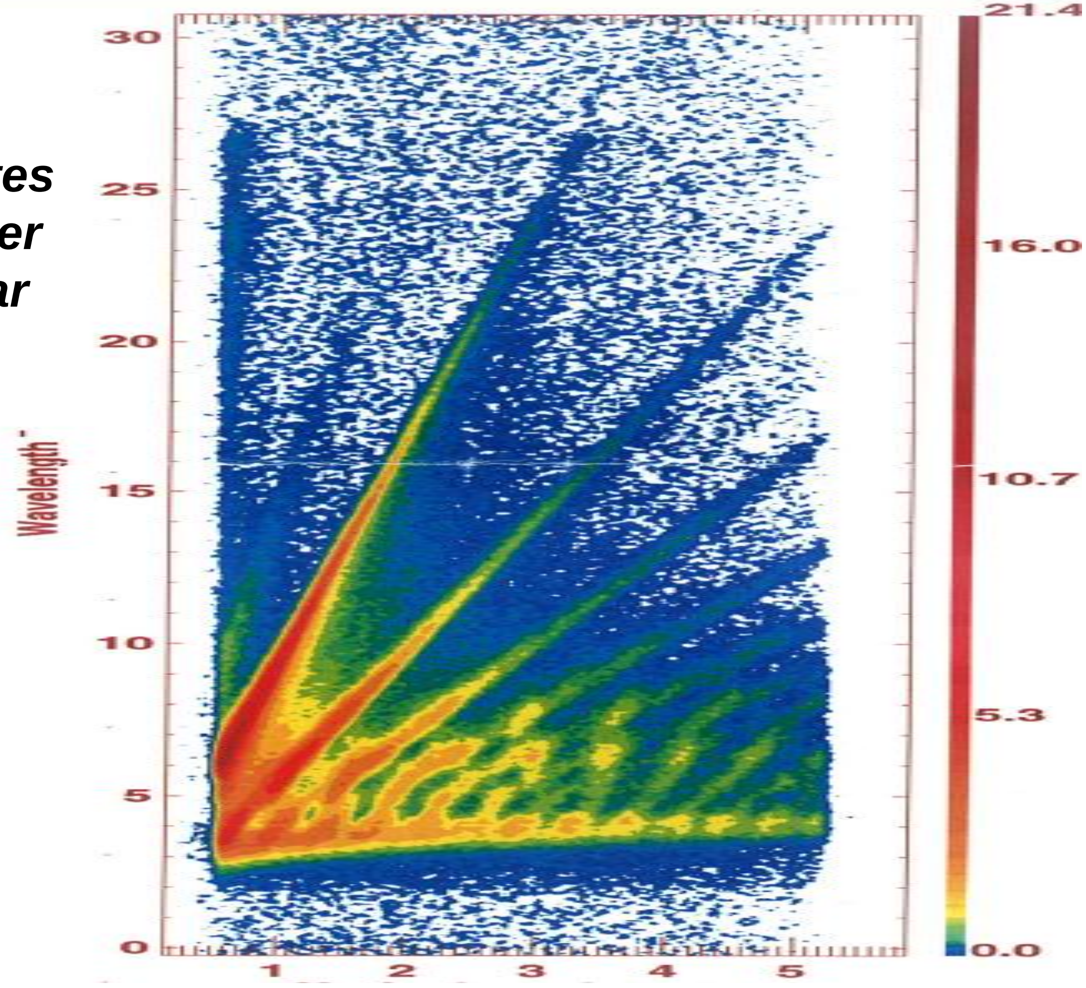
theory/experiment



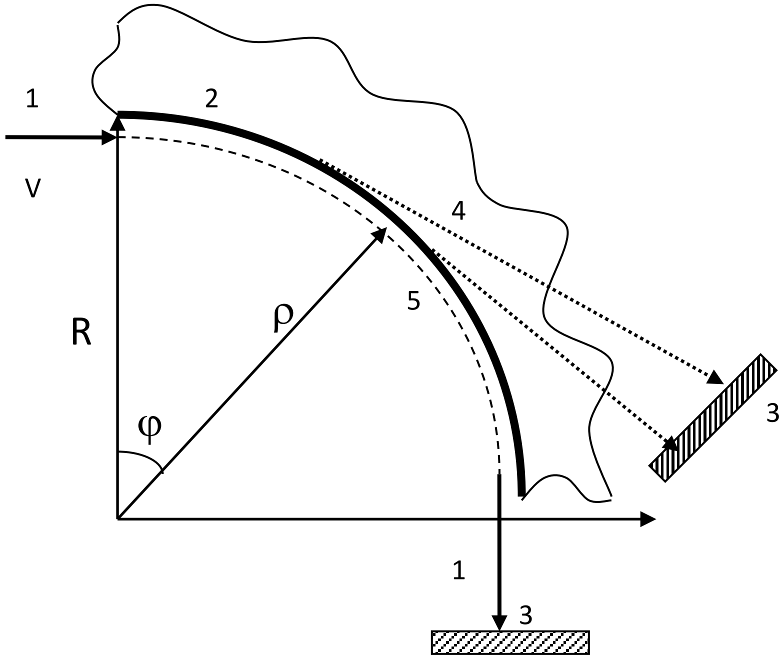


Neutrons tunneling OUT of quantum states

Neutrons populate quantum states states through edges of a truccated cylinder and tunnel out through the triangular potential barrier



Methods of observation



D17 instrument at the ILL

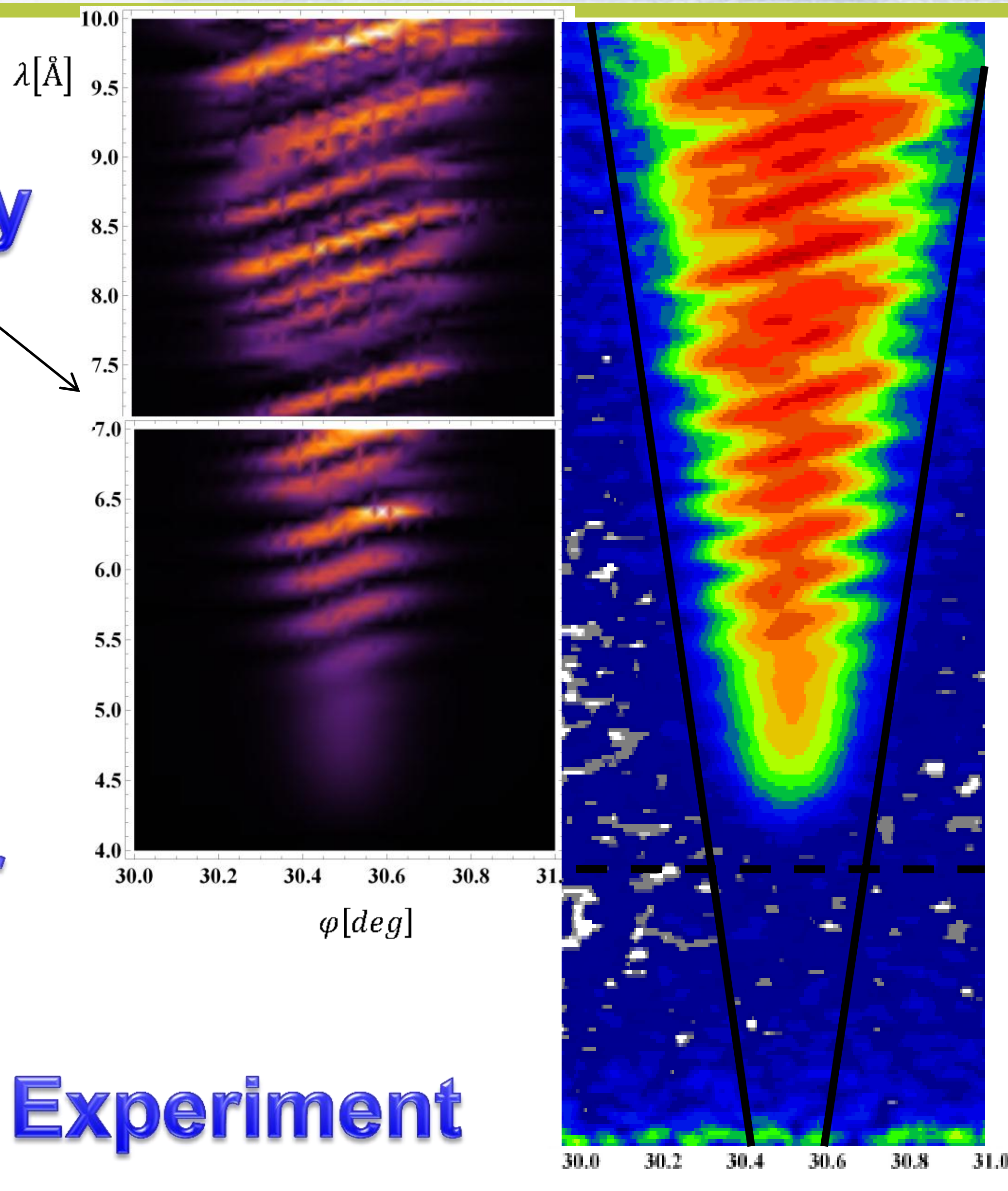
Neutrons entering from edge of truncated cylindrical mirror

1) *Tangential neutron velocity is defined by time-of-flight method;*

2) *Scattering angle (radial velocity) is measured in a position-sensitive neutron detector.*

Results

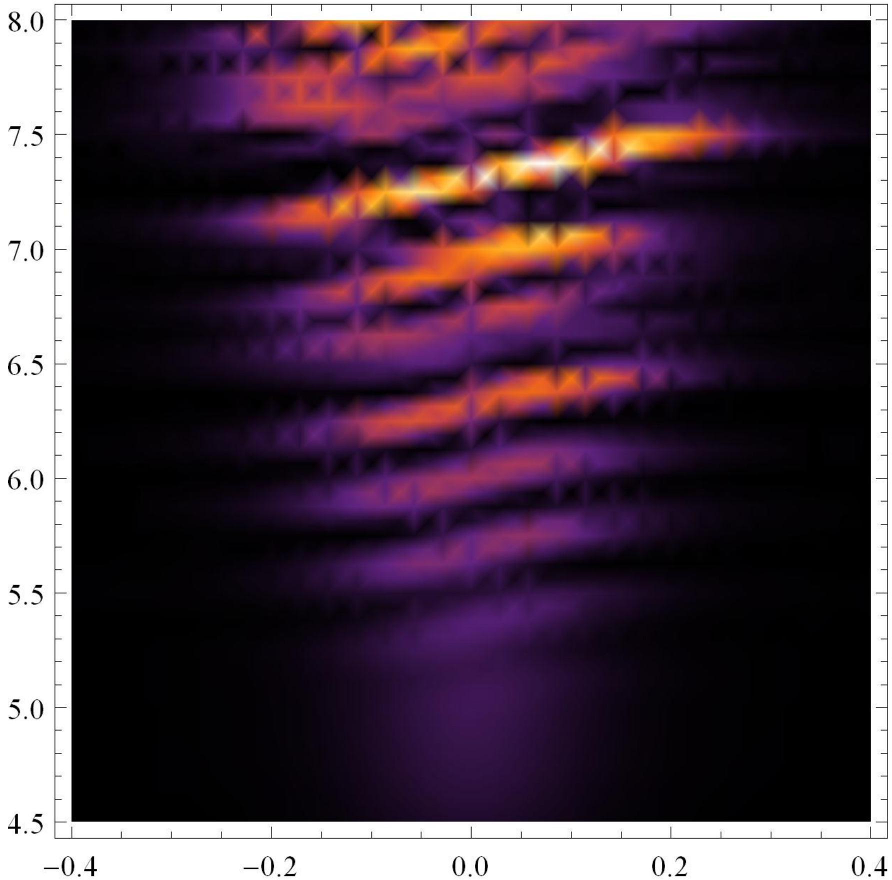
Theory

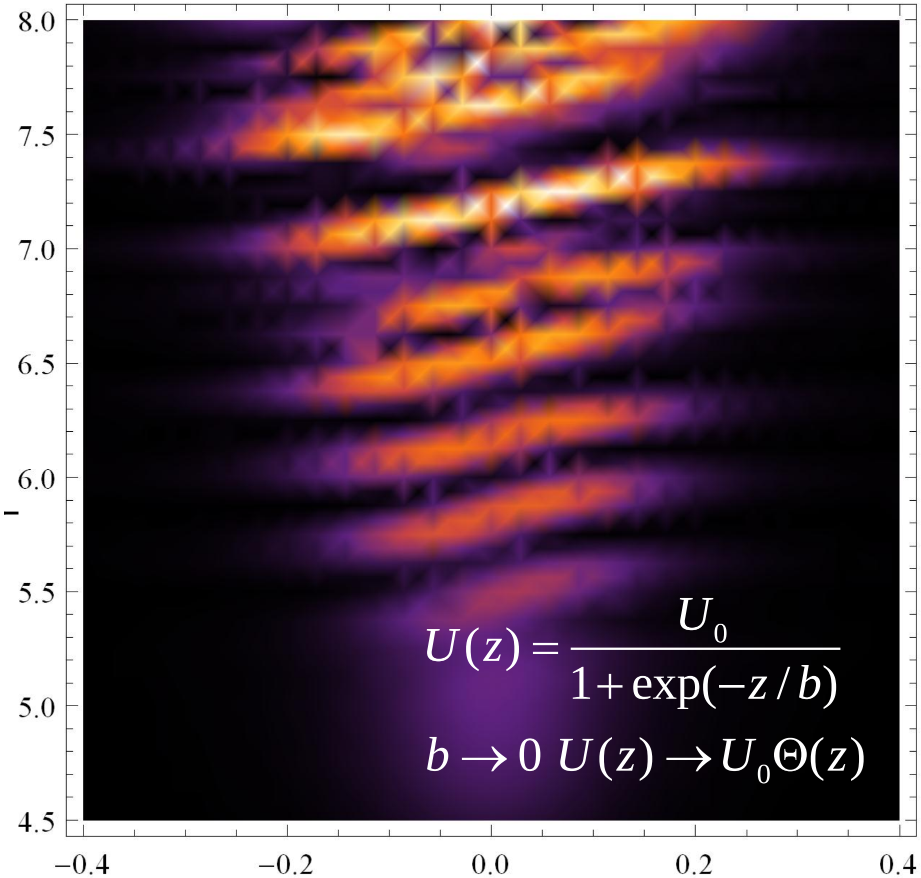


Neutrons entering from mirror edge

Experiment

Sensivity to additional forces

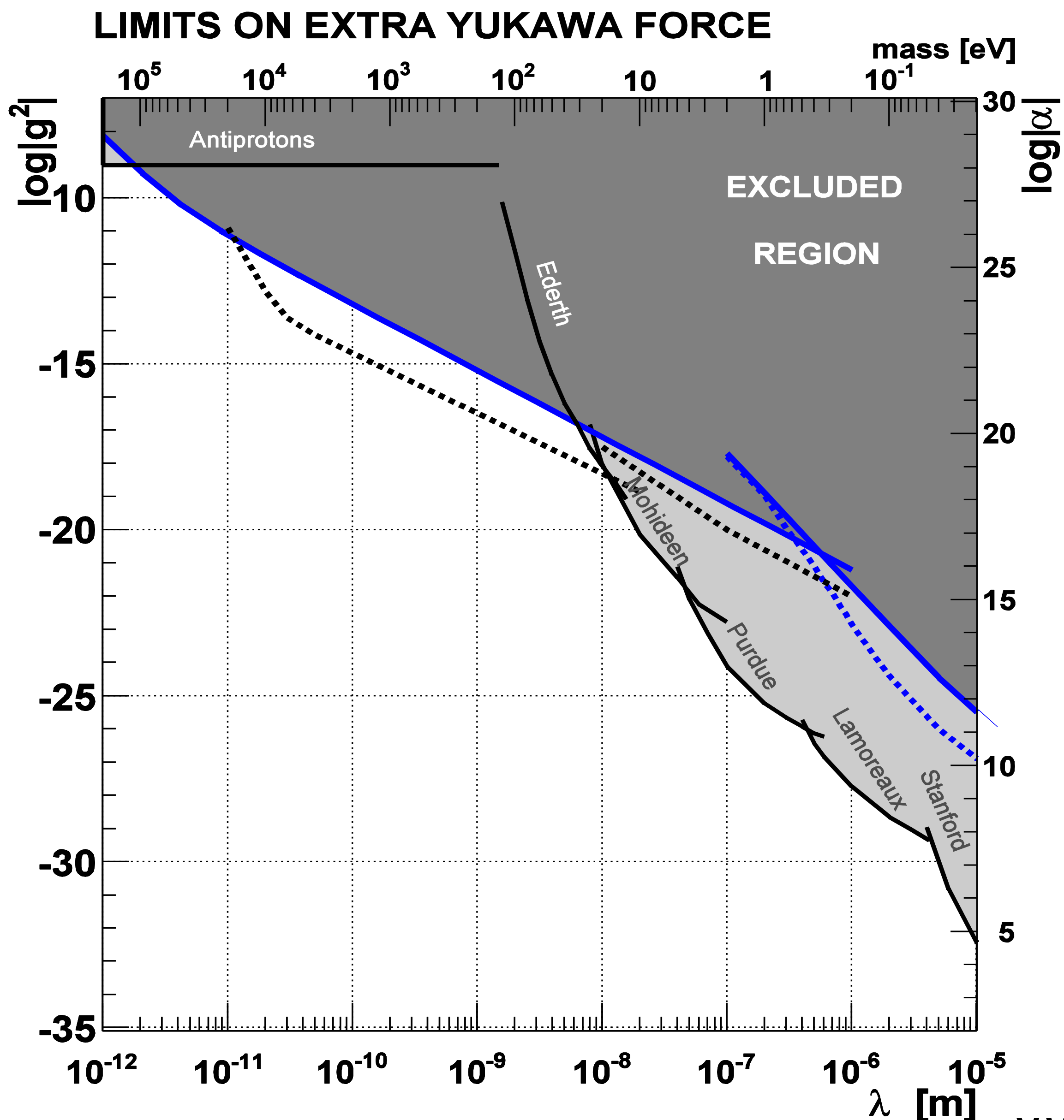




b=0

b=4nm

Sensitivity to additional forces

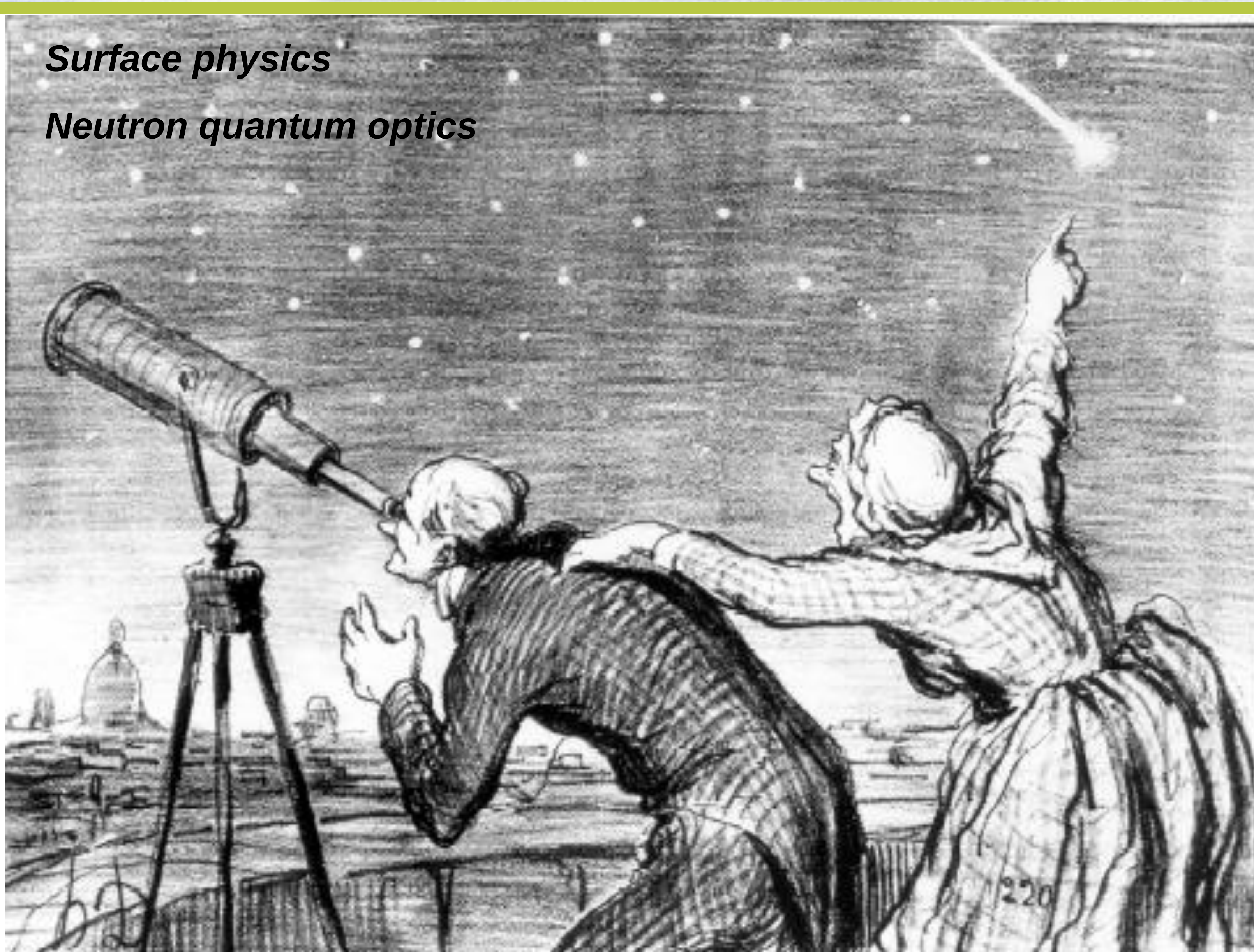


V.V. Nesvizhevsky

Applications

Surface physics

Neutron quantum optics

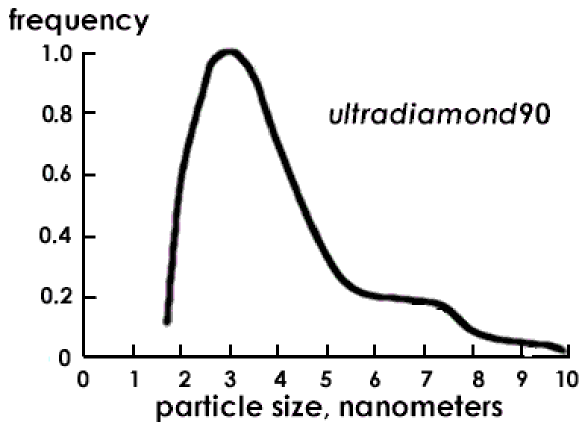


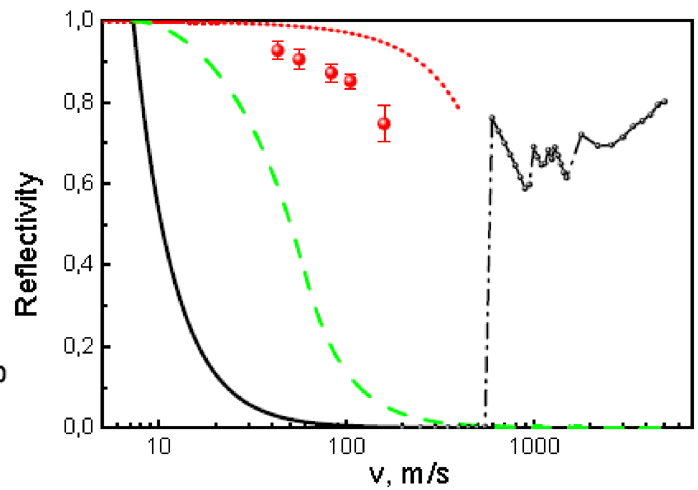
Conclusion (on centrifugal quantum states)

1. First observation of quasi-stationary quantum states of cold neutrons in vicinity of curved mirror surface: neutron whispering gallery
2. First direct demonstration of the weak equivalence for an object in a quantum state.
3. Long lifetimes of neutrons in the quantum states allow us to use this phenomenon for precision studies of surface potentials and probably for constraining fundamental short-range potentials

Nanoparticle-powder reflectors for cold and very cold neutrons

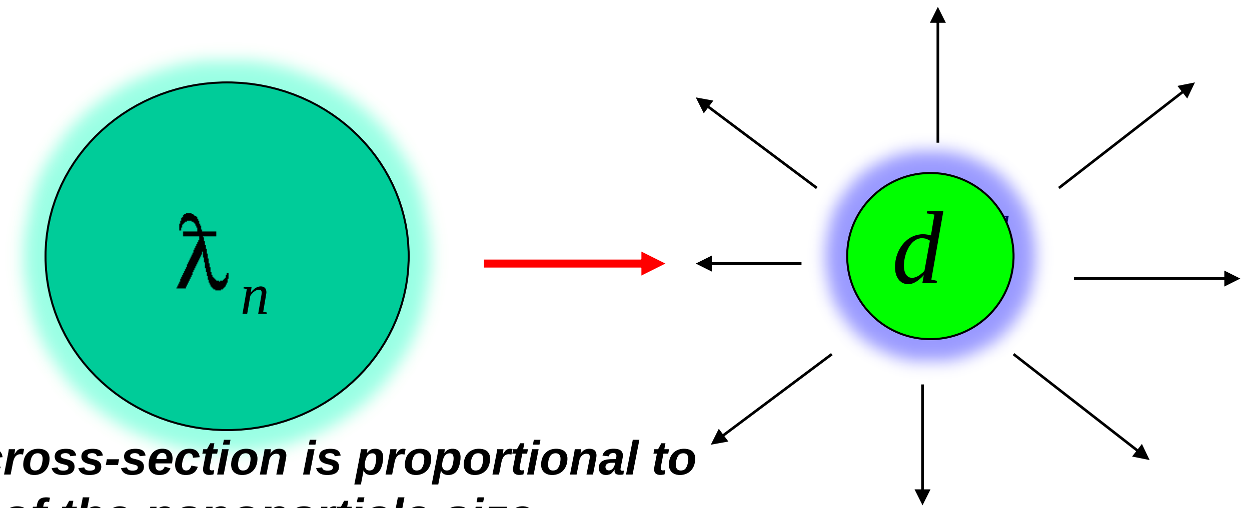
1. ***Neutron scattering on nanoparticles.***
2. ***Reflection of very cold neutrons (VCN) from nanoparticle powders.***
3. ***Storage of VCN in traps.***
4. ***Quasi-specular reflection of cold neutrons from powders.***
5. ***Possible applications.***
6. ***Behavior of nanoparticles in high radiation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



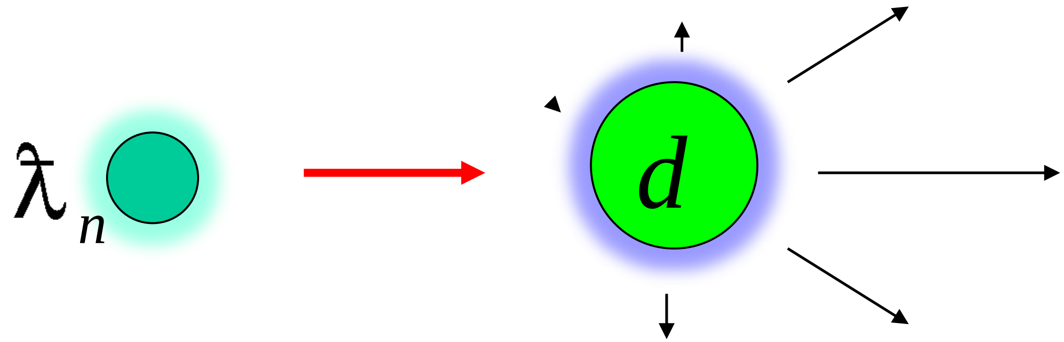


Neutron scattering on nanoparticles

Optimum: neutron wavelength λ_n *is approximately equal to the nanoparticle size* d

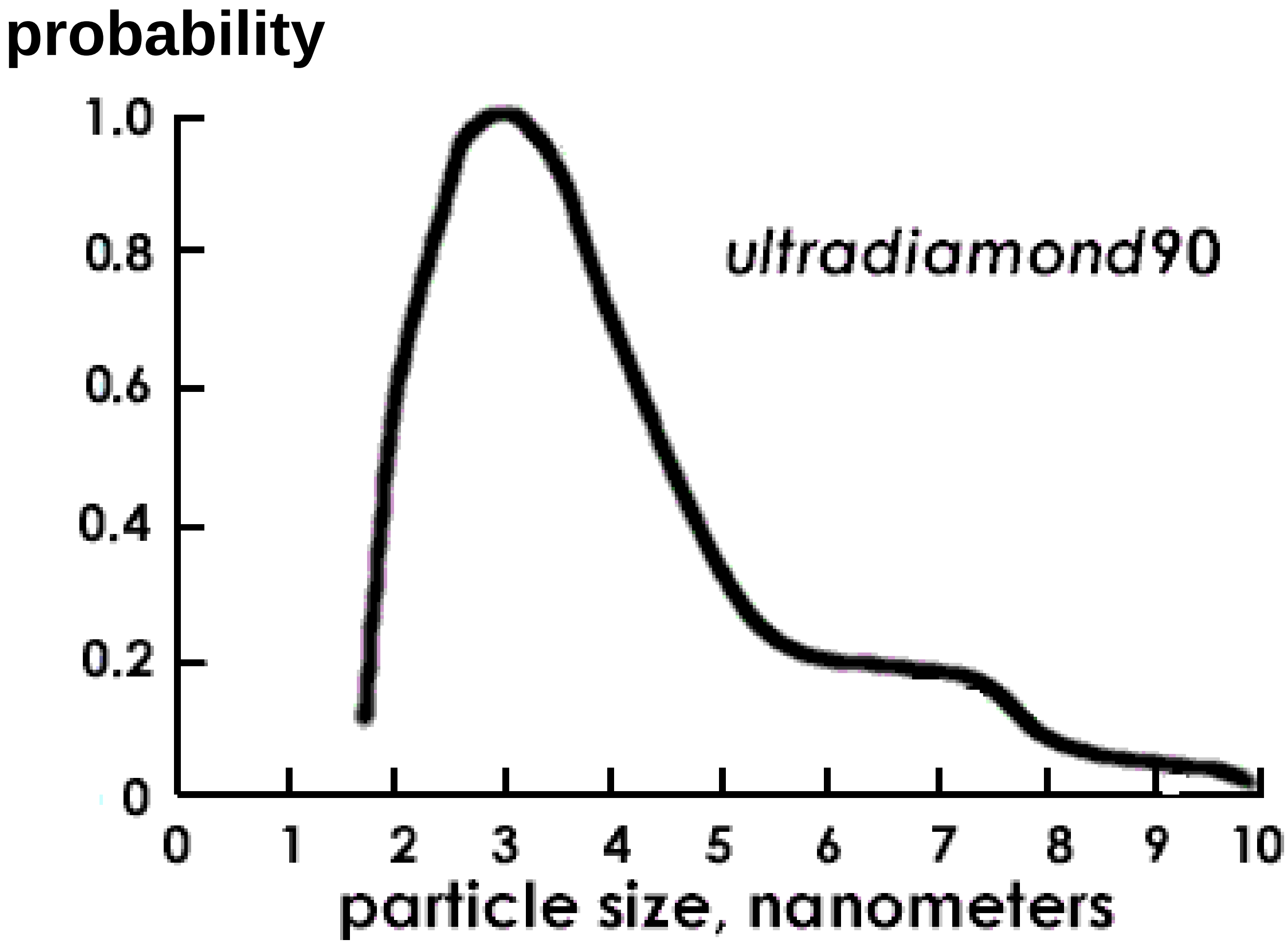


the scattering cross-section is proportional to 6-th power of the nanoparticle size



Neutron scattering on nanoparticles
Diamond nanoparticles

Diamond nanoparticles is an evident candidate because of exceptionally high optical potential of diamond; nanoparticles of diamond are available in powders; such powders are not too expensive



Neutron scattering on nanoparticles
Theoretical description

V.V. N., G. Pignol and K.V. Protasov (2007). "Nanoparticles as a possible moderator for an ultracold neutron source." International Journal of Nanoscience ***6(6): 485-499.***

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

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

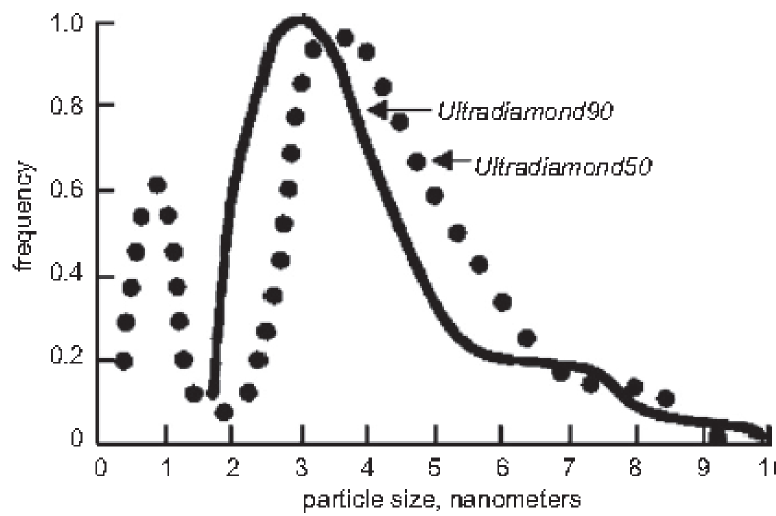


Fig. 4. The size distribution of the diamond nanoparticles in the powder "ultradiamond90".

Neutron scattering on nanoparticles
Theoretical description

V.V. N., G. Pignol and K.V. Protasov (2007). "Nanoparticles as a possible moderator for an ultracold neutron source." International Journal of Nanoscience ***6(6): 485-499.***

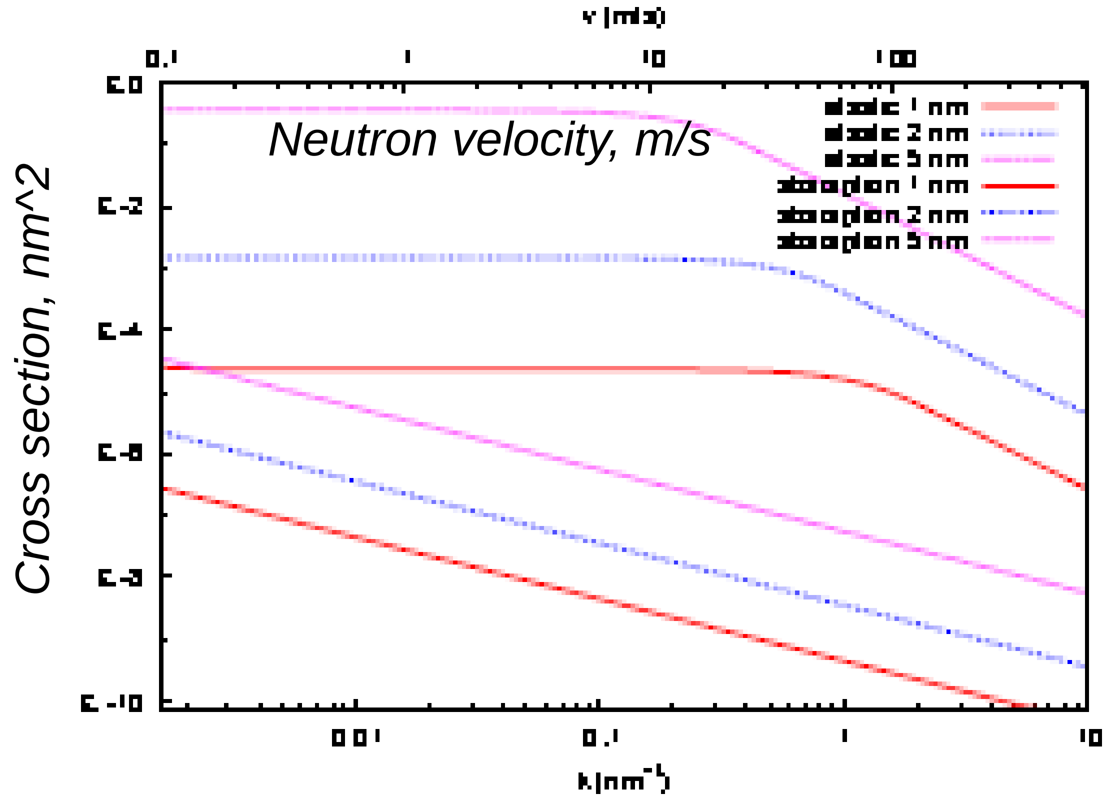


FIG. 1: Elastic and absorption cross sections as a function of neutron velocity, for three values of the deuterium nanoparticles' radii: 1, 2, and 5 nm.

Neutron scattering on nanoparticles
Intermediate conclusion

*V.V. N., G. Pignol and K.V. Protasov (2007). "Nanoparticles as a possible moderator for an ultracold neutron source." International Journal of Nanoscience **6(6): 485-499.***

- ***Analytical theoretical description is available***
- ***Diamond is the optimum material***
- ***The optimum nanoparticle size is about 5nm***

Reflection of very cold neutrons from the powders
Scheme of the experiment

V.V. N., E.V. Lychagin, A.Yu. Muzychka, A.V. Strelkov, G. Pignol, and K.V. Protasov (2008). "The reflection of very cold neutrons from diamond powder nanoparticles." Nuclear Instruments and Methods A ***595: 631-636.***

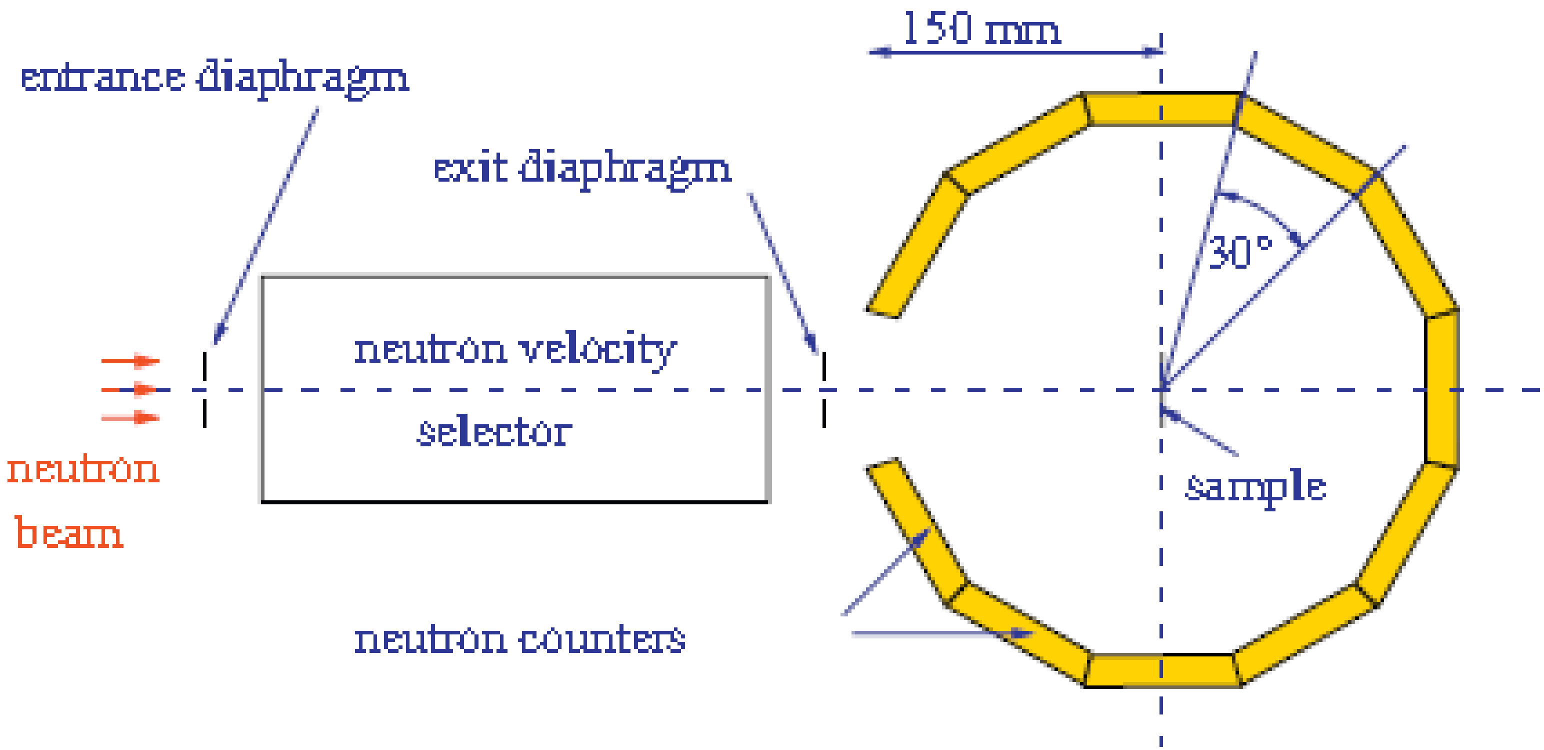
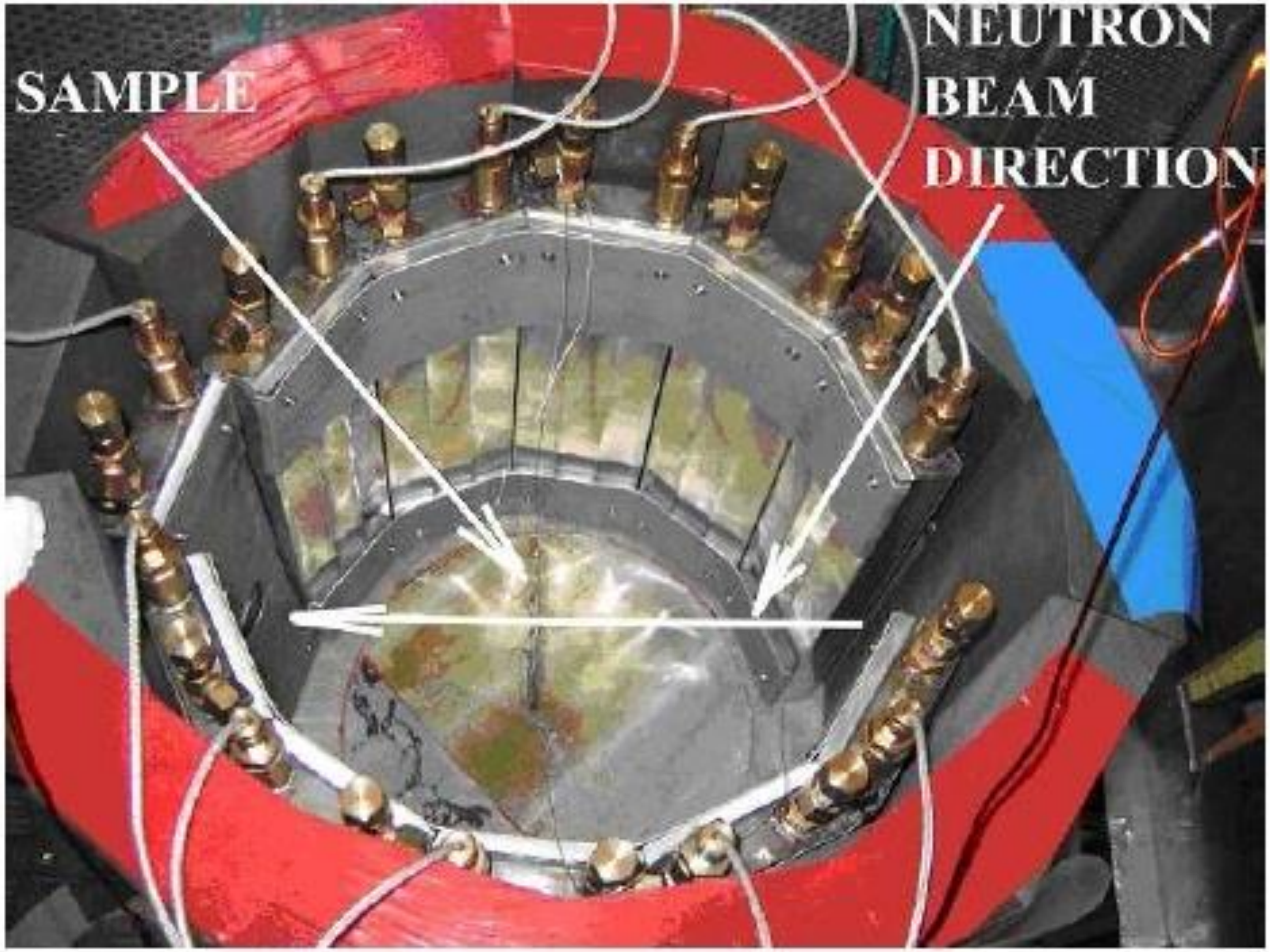


Fig. 1. The experimental setup (view from above).

Reflection of very cold neutrons from the powders
Experimental setup

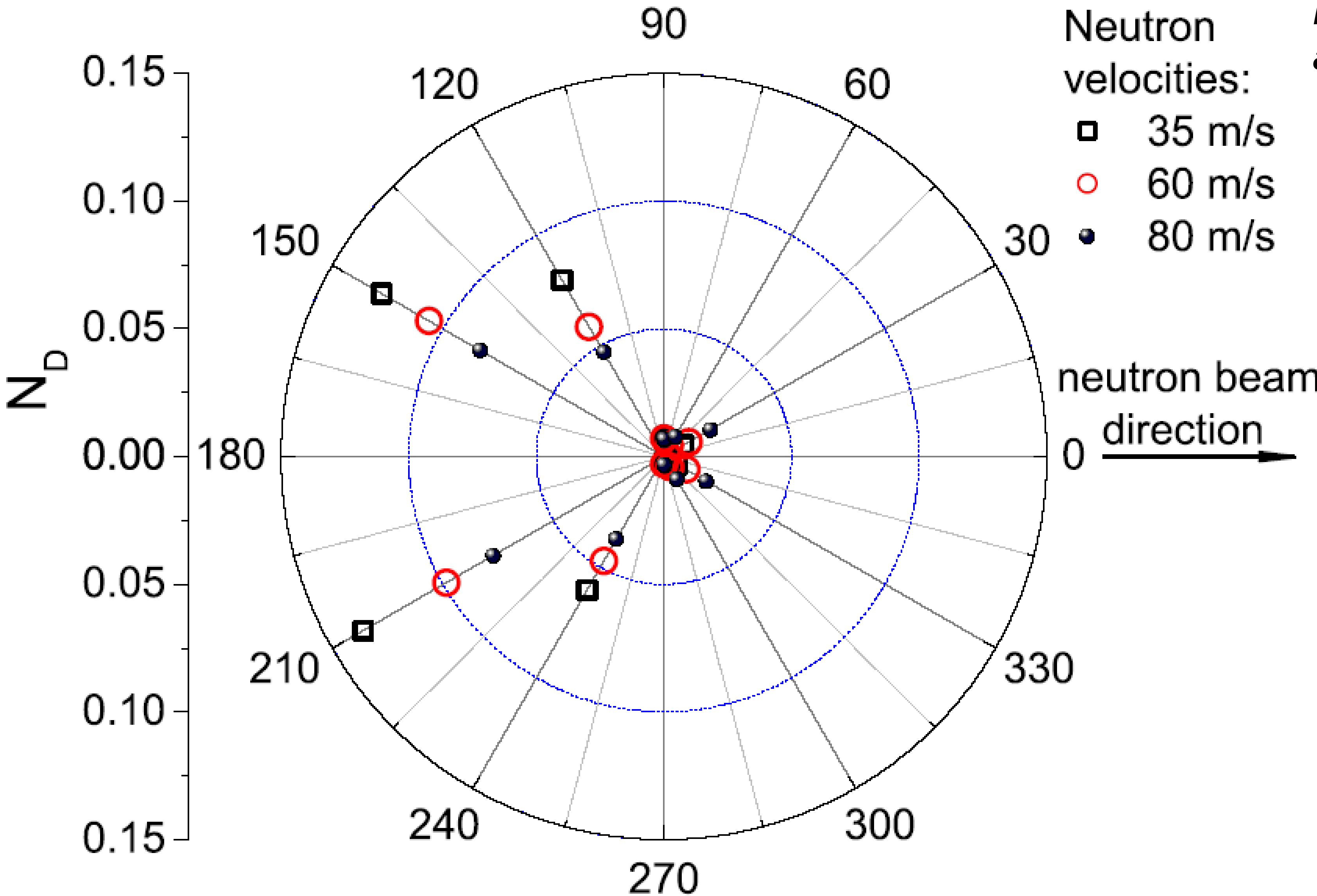
V.V. N., E.V. Lychagin, A.Yu. Muzychka, A.V. Strelkov, G. Pignol, and K.V. Protasov (2008). "The reflection of very cold neutrons from diamond powder nanoparticles." Nuclear Instruments and Methods A ***595: 631-636.***



Reflection of very cold neutrons from the powders
Experimental results

Scattering is very efficient !

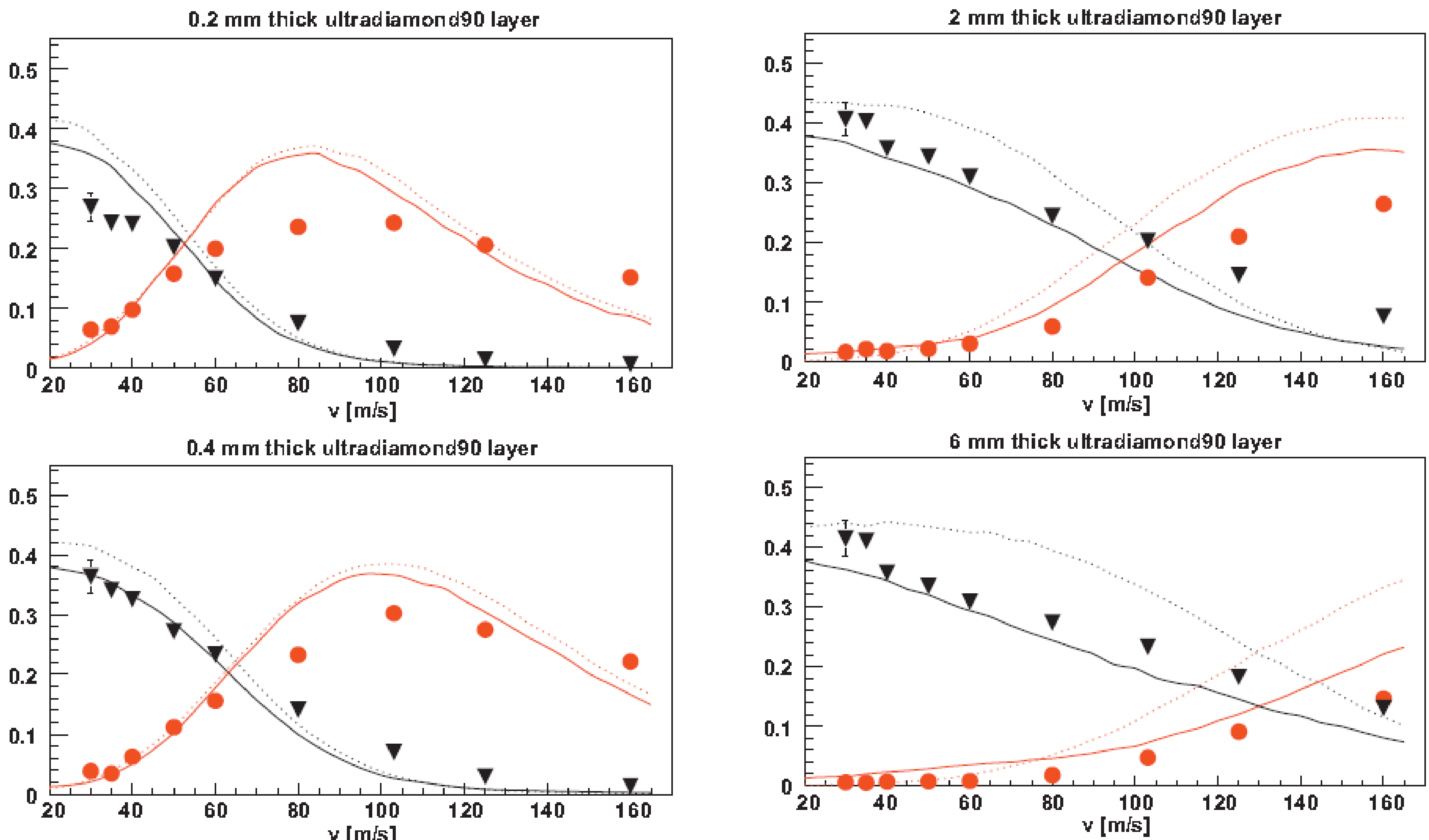
PF2 instrument at the ILL



Nesvizhevsky

Reflection of very cold neutrons from the powders
Experimental results

Scattering is very efficient ! ***PF2***



Reflection of very cold neutrons from the powders
Experimental results

Scattering is elastic !

PF2

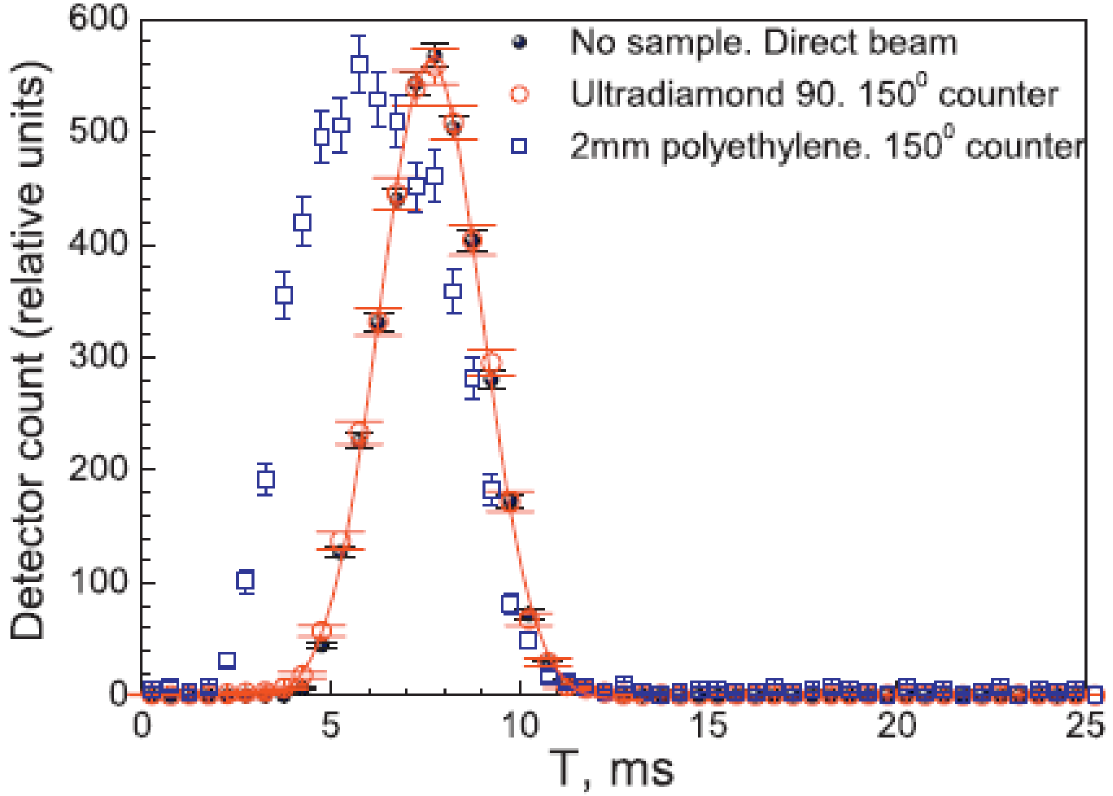


Fig. 6. The neutron count rate is presented as a function of the time of flight of the neutrons with an average initial velocity of 60 m/s. The zero time is synchronized with opening the chopper. The black circles correspond to the initial neutron spectrum. The empty circles indicate the data for the 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.

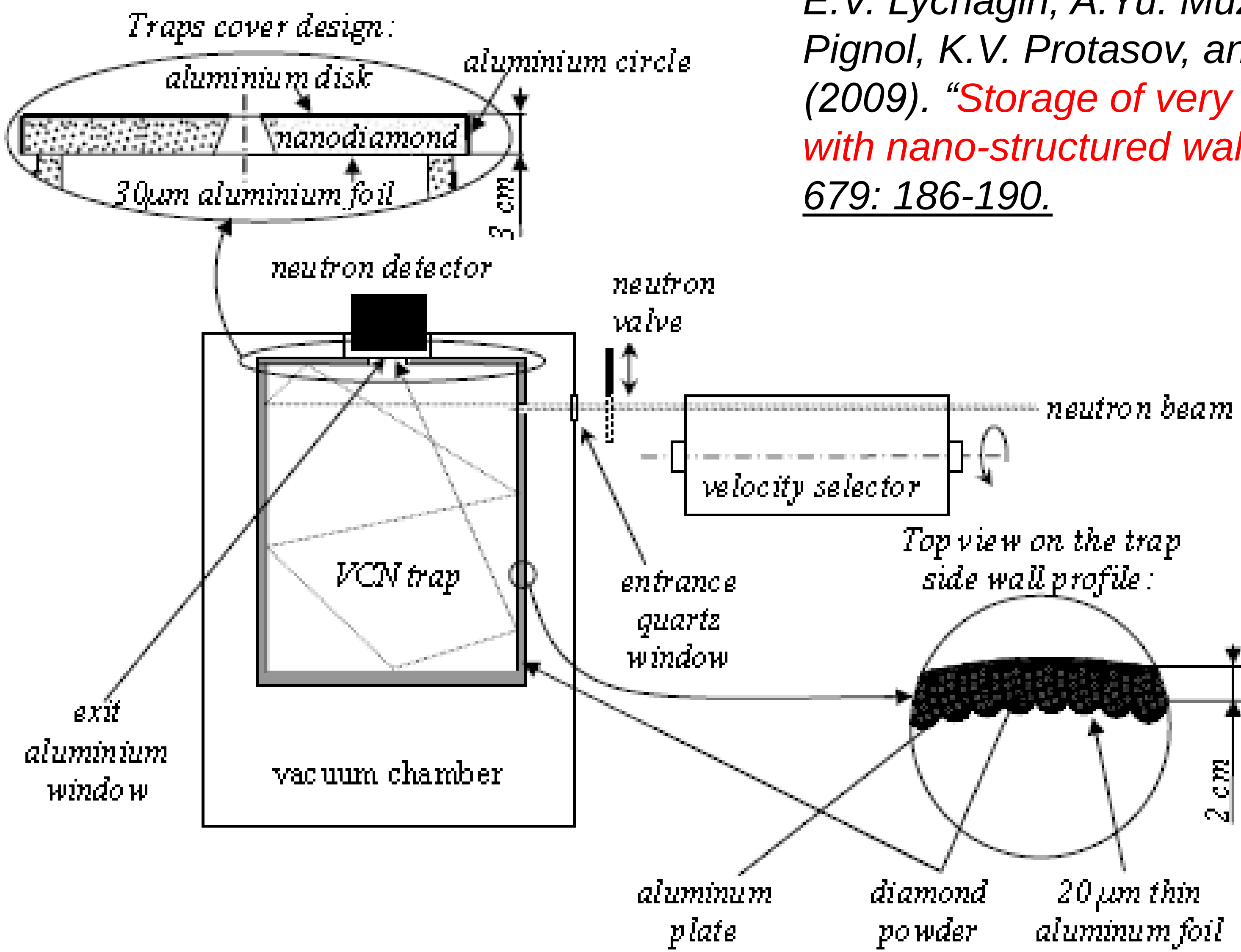
Reflection of very cold neutrons from the powders
Intermediate conclusion

V.V. N., E.V. Lychagin, A.Yu. Muzychka, A.V. Strelkov, G. Pignol, and K.V. Protasov (2008). "The reflection of very cold neutrons from diamond powder nanoparticles." Nuclear Instruments and Methods A ***595: 631-636.***

- ***High efficiency of reflection of very cold neutrons from powders of diamond nanoparticles is proven experimentally***
- ***The reflection is elastic***

Storage of very cold neutrons in traps
Scheme of the experiment

E.V. Lychagin, A.Yu. Muzychka, V.V. N., G. Pignol, K.V. Protasov, and A.V. Strelkov (2009). "Storage of very cold neutrons in a trap with nano-structured walls." Physics Letters A 679: 186-190.



Storage of very cold neutrons in traps
Experimental setup

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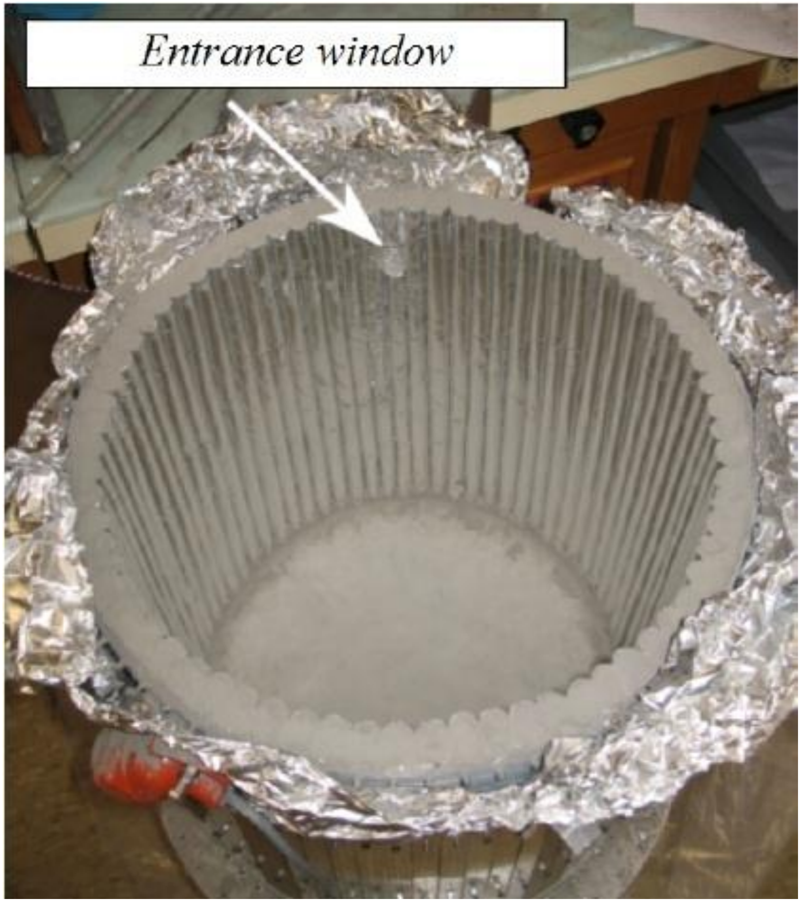

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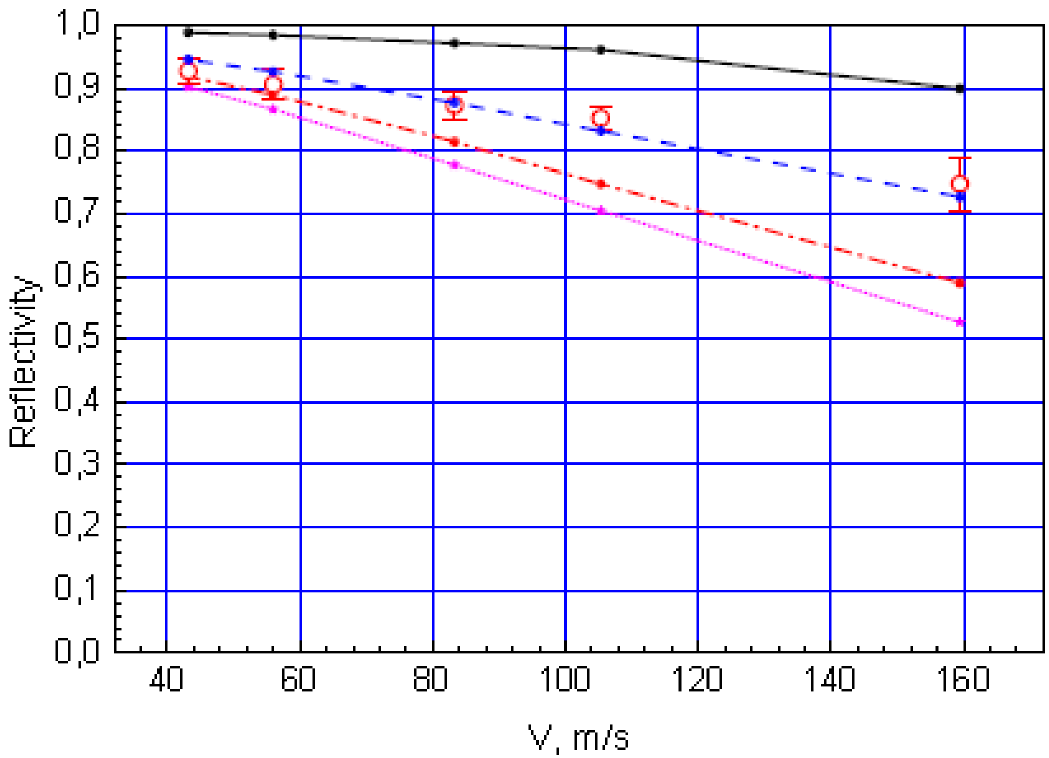
PF2



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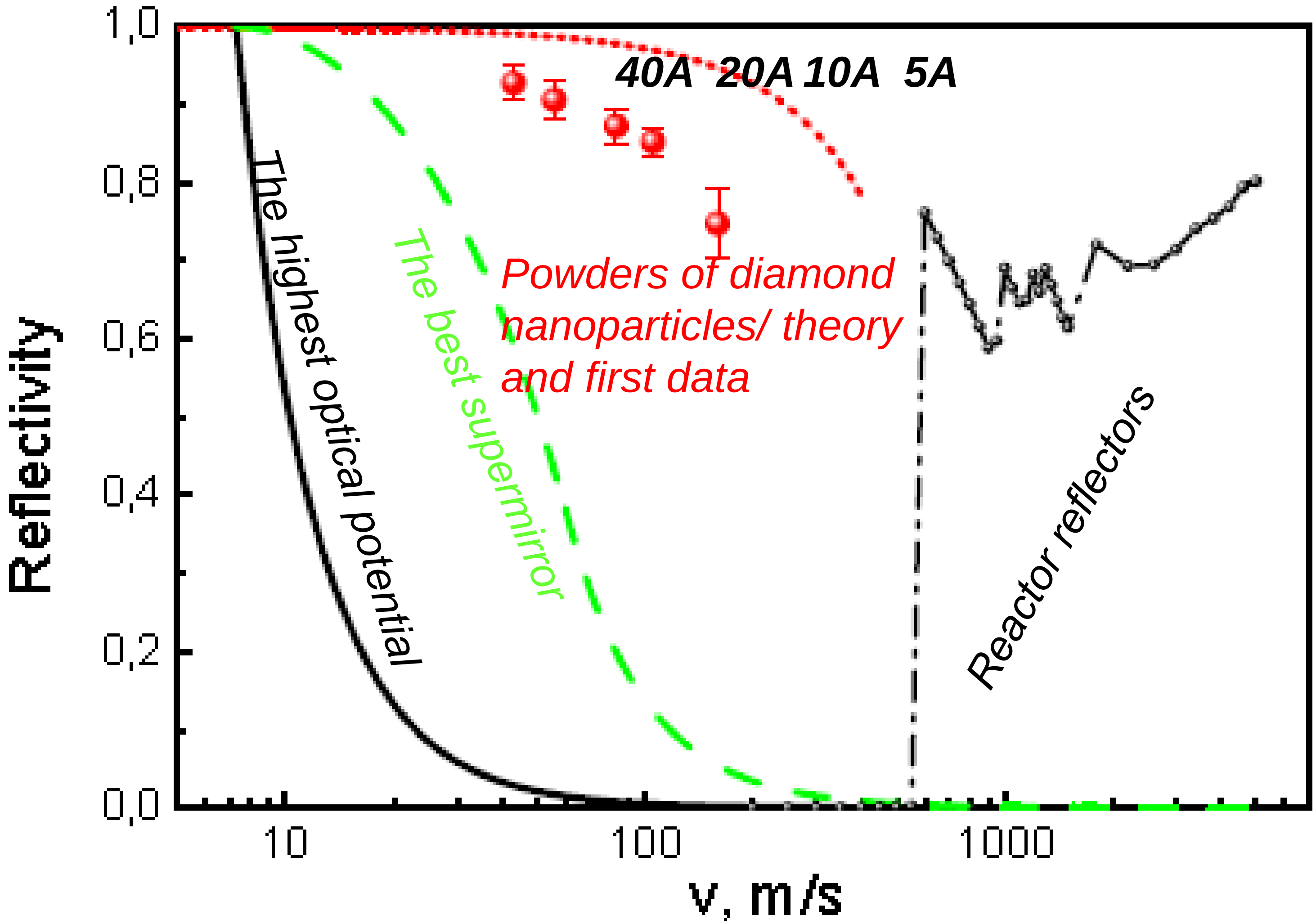


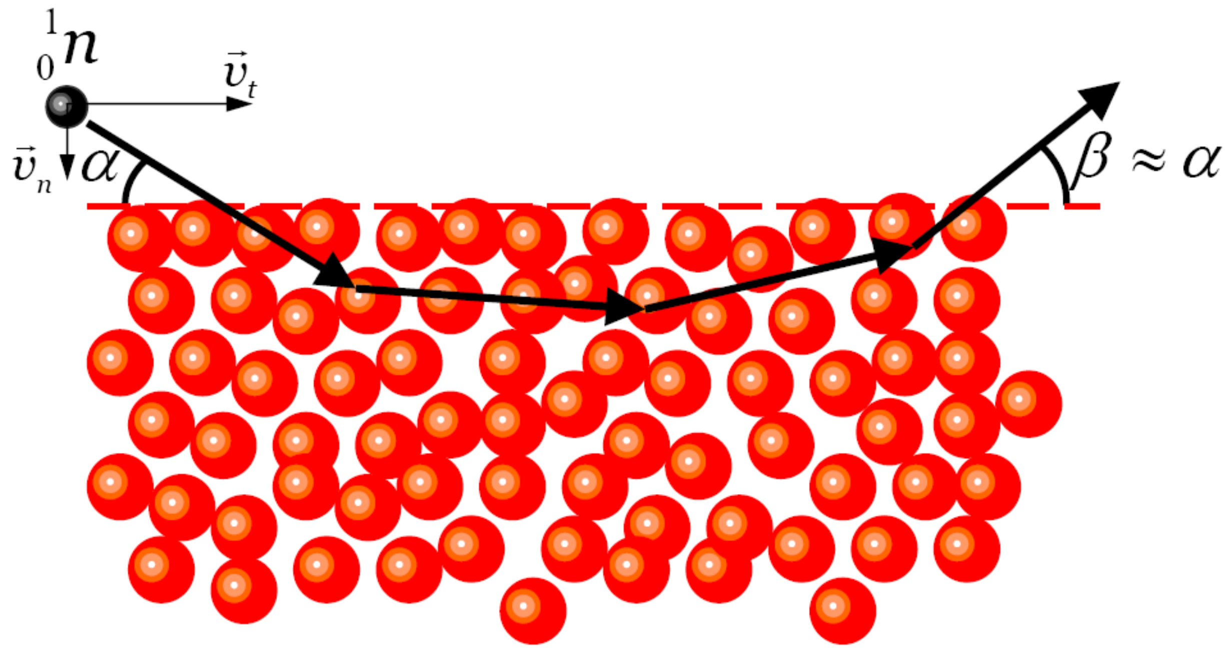
Storage of very cold neutrons in traps
Intermediate conclusion

E.V. Lychagin, A.Yu. Muzychka, V.V. N., G. Pignol, K.V. Protasov, and A.V. Strelkov (2009). "Storage of very cold neutrons in a trap with nano-structured walls." Physics Letters A 679: 186-190.

- ***The probability of reflection of very cold neutrons from powder of diamond nanoparticles is measured as a function of the neutron velocity and the powder treatment***
- ***Very cold neutrons can be stored in closed traps !***
- ***The powders of nanoparticles "bridge the gap" between supermirrors and reflectors for thermal neutrons***

Quasi-specular reflection of cold neutrons from powders

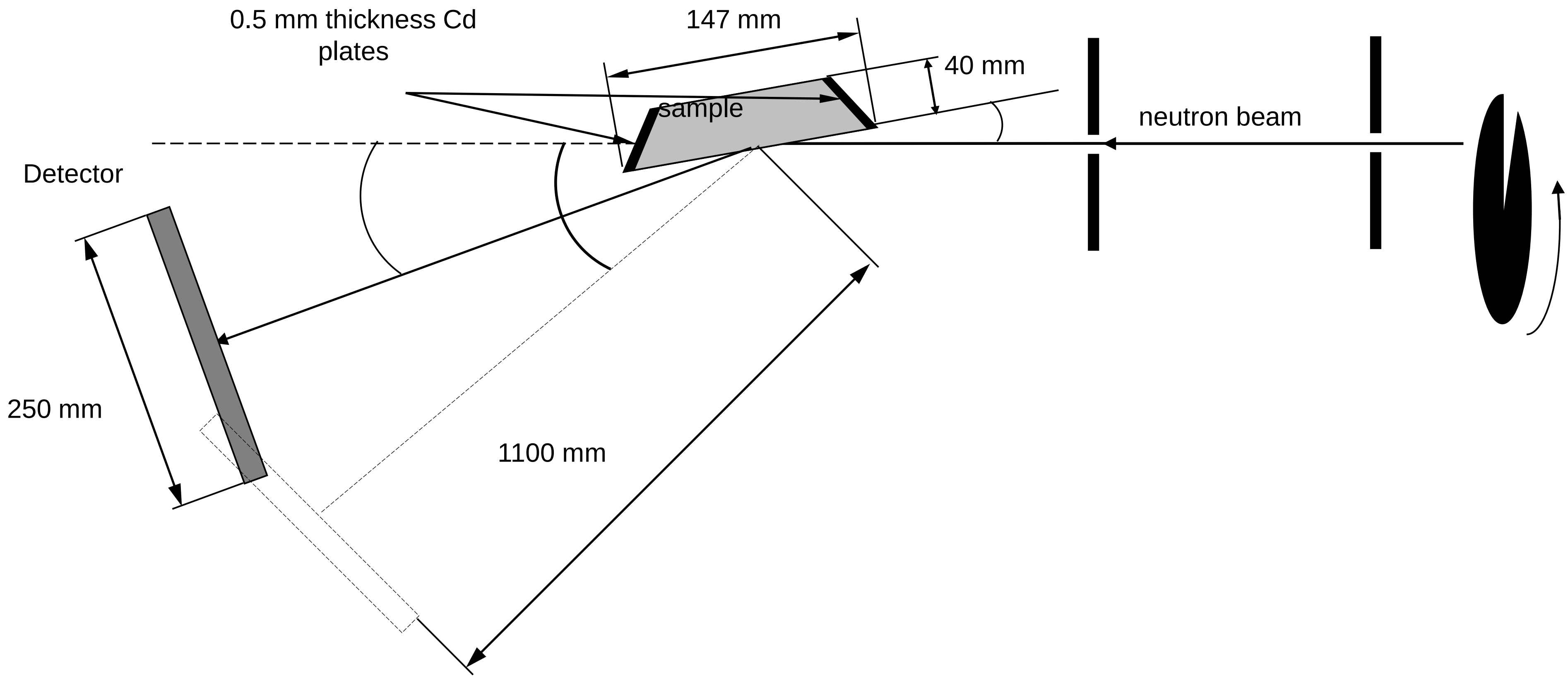
V.V. N., R. Cubitt, E.V. Lychagin, A.Yu. Muzychka, G.V. Nekhaev, G. Pignol, K.V. Protasov, and A.V. Strelkov (2010). « Application of diamond nanoparticles in low-energy neutron physics. » <u>Materials 3:1768-1781</u>



Quasi-specular reflection of cold neutrons from powders
Scheme of the experiment

V.V. N., R. Cubitt, E.V. Lychagin, A.Yu. Muzychka, G.V. Nekhaev, G. Pignol, K.V. Protasov, and A.V. Strelkov (2010). « *Application of diamond nanoparticles in low-energy neutron physics.* » Materials 3:1768-1781

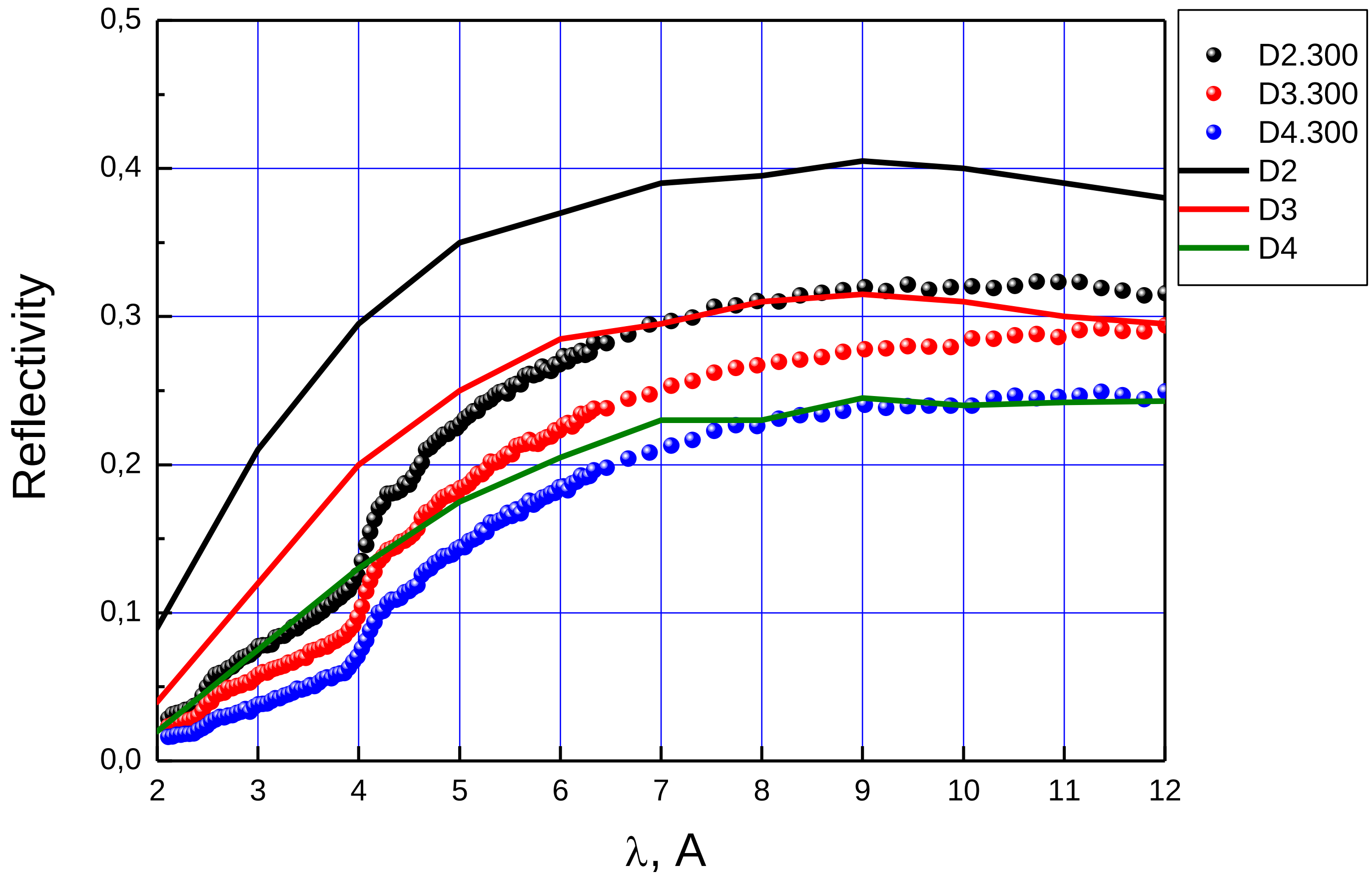
D17



Quasi-specular reflection of cold neutrons from powders
Experimental results

NEUTRONS FOR SCIENCE

V.V. N., R. Cubitt, E.V. Lychagin, A.Yu. Muzychka, G.V. Nekhaev, G. Pignol, K.V. Protasov, and A.V. Strelkov (2010). « Application of diamond nanoparticles in low-energy neutron physics. » <u>Materials 3:1768-1781</u>



Quasi-specular reflection of cold neutrons from powders
Experimental results

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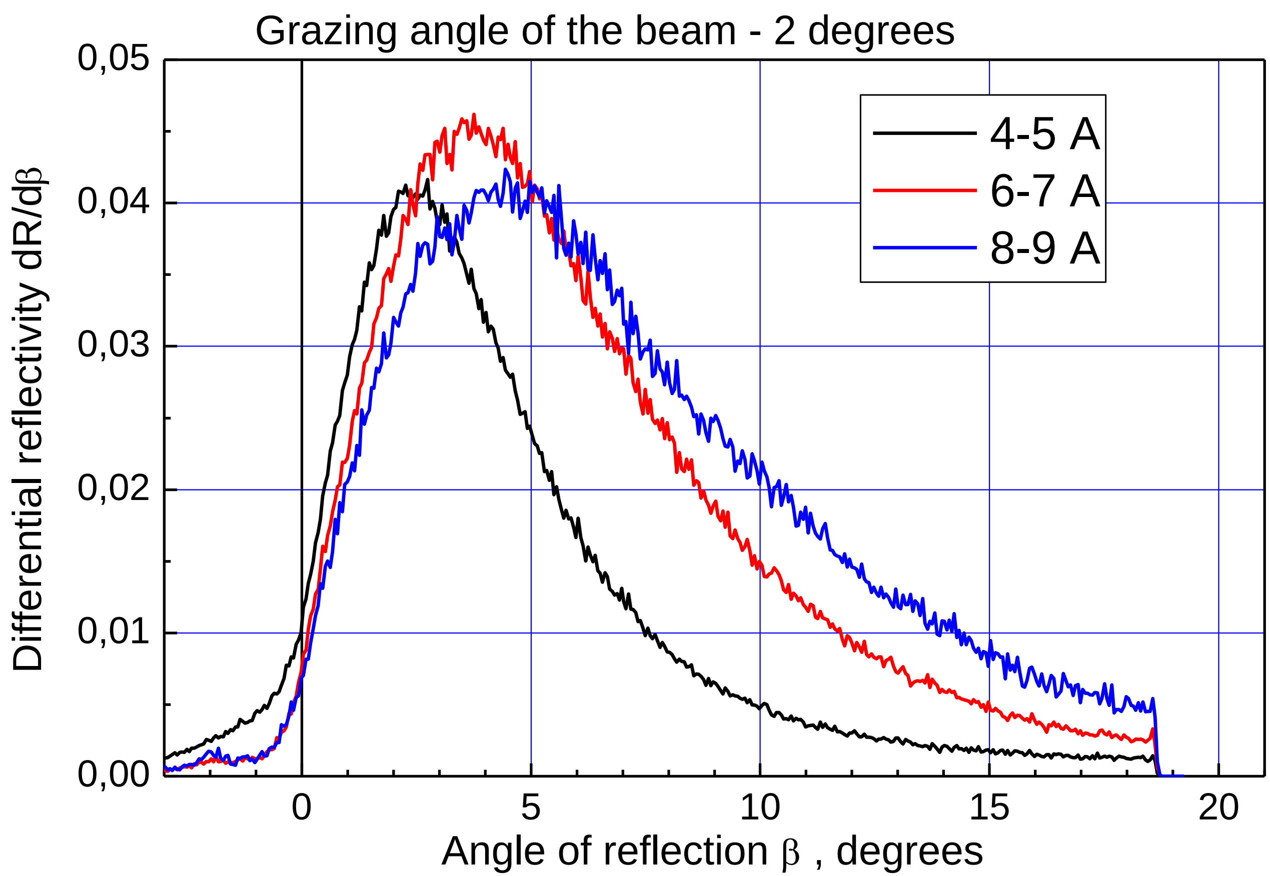
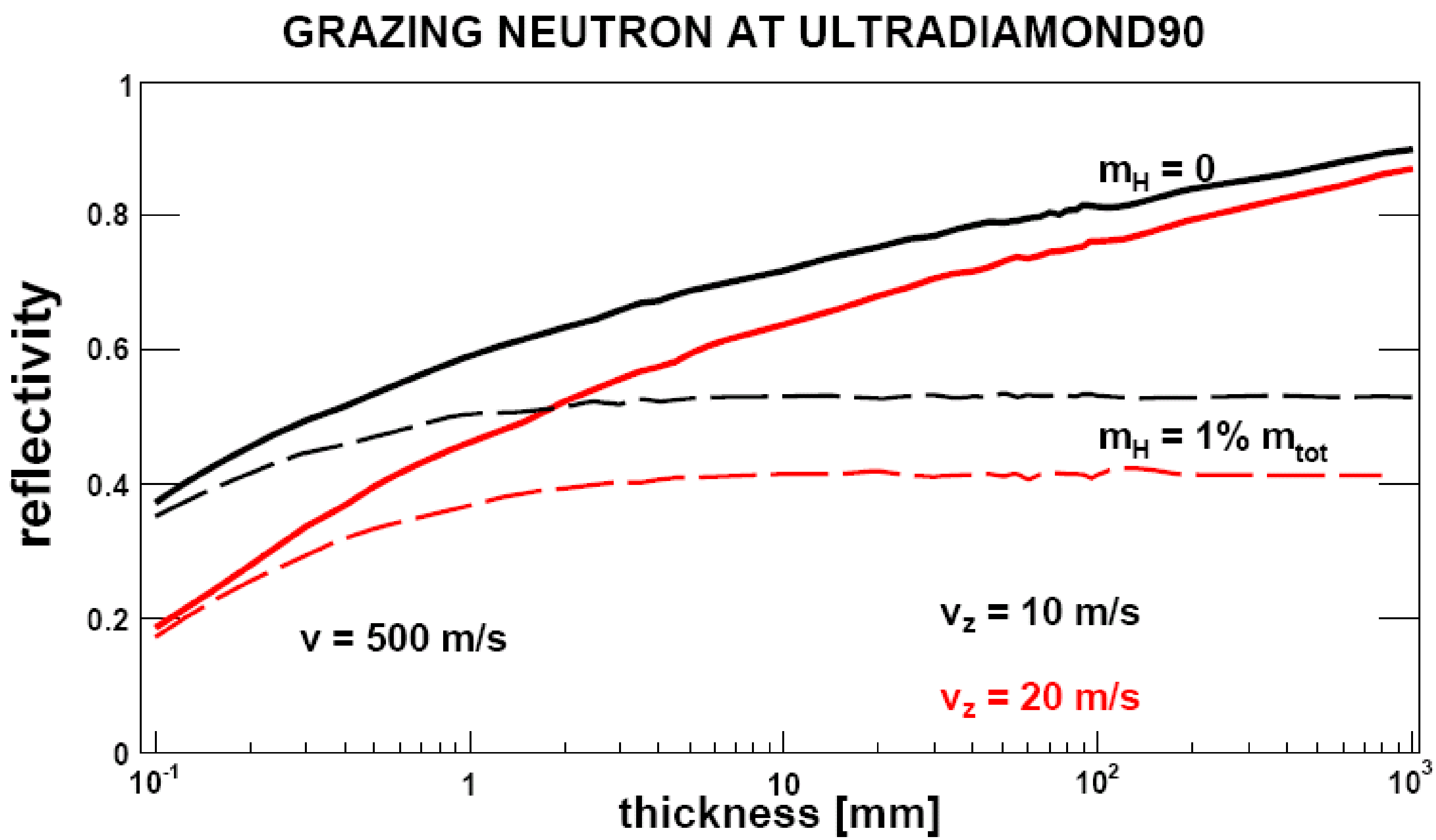


Quasi-specular reflection of cold neutrons from powders
Simulation

V.V. N., R. Cubitt, E.V. Lychagin, A.Yu. Muzychka, G.V. Nekhaev, G. Pignol, K.V. Protasov, and A.V. Strelkov (2010). « Application of diamond nanoparticles in low-energy neutron physics. » Materials 3:1768-1781

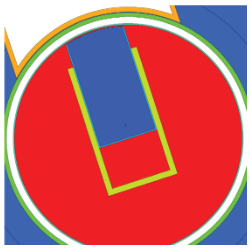


Quasi-specular reflection of cold neutrons from powders
Intermediate conclusion

V.V. N., R. Cubitt, E.V. Lychagin, A.Yu. Muzychka, G.V. Nekhaev, G. Pignol, K.V. Protasov, and A.V. Strelkov (2010). « Application of diamond nanoparticles in low-energy neutron physics. » Materials 3:1768-1781

- ***The probability of reflection of cold neutrons from powder of diamond nanoparticles is measured at small grazing angles as a function of the neutron velocity, the grazing angle, and the nanoparticles temperature***
- ***New phenomenon of quasi-specular small-angle reflection (albedo) of cold neutrons from nanoparticle powder is observed!***
- ***This phenomenon could be used in neutron optics for shaping neutron beams***

Possible applications for sources of UCN, VCN and cold neutrons



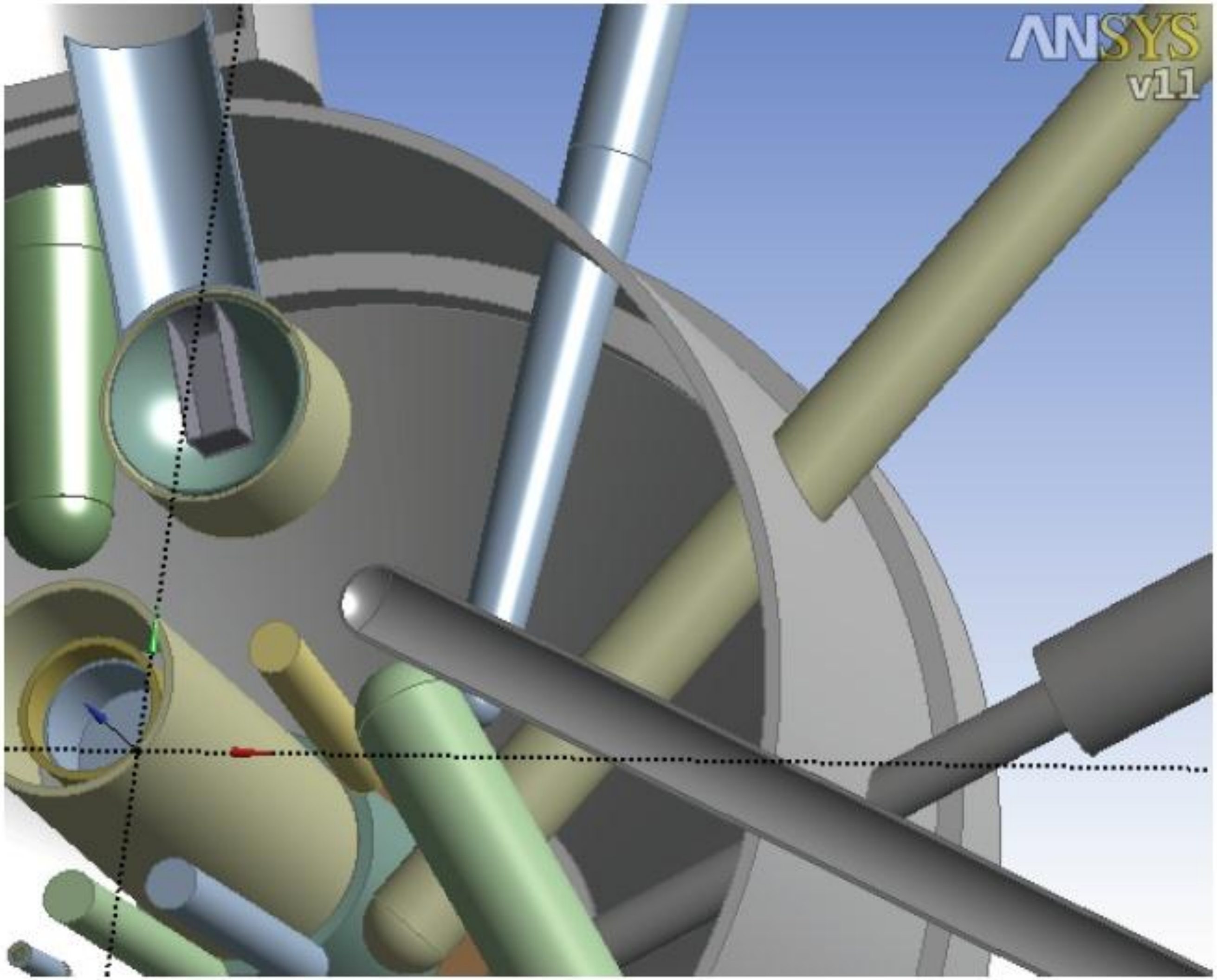
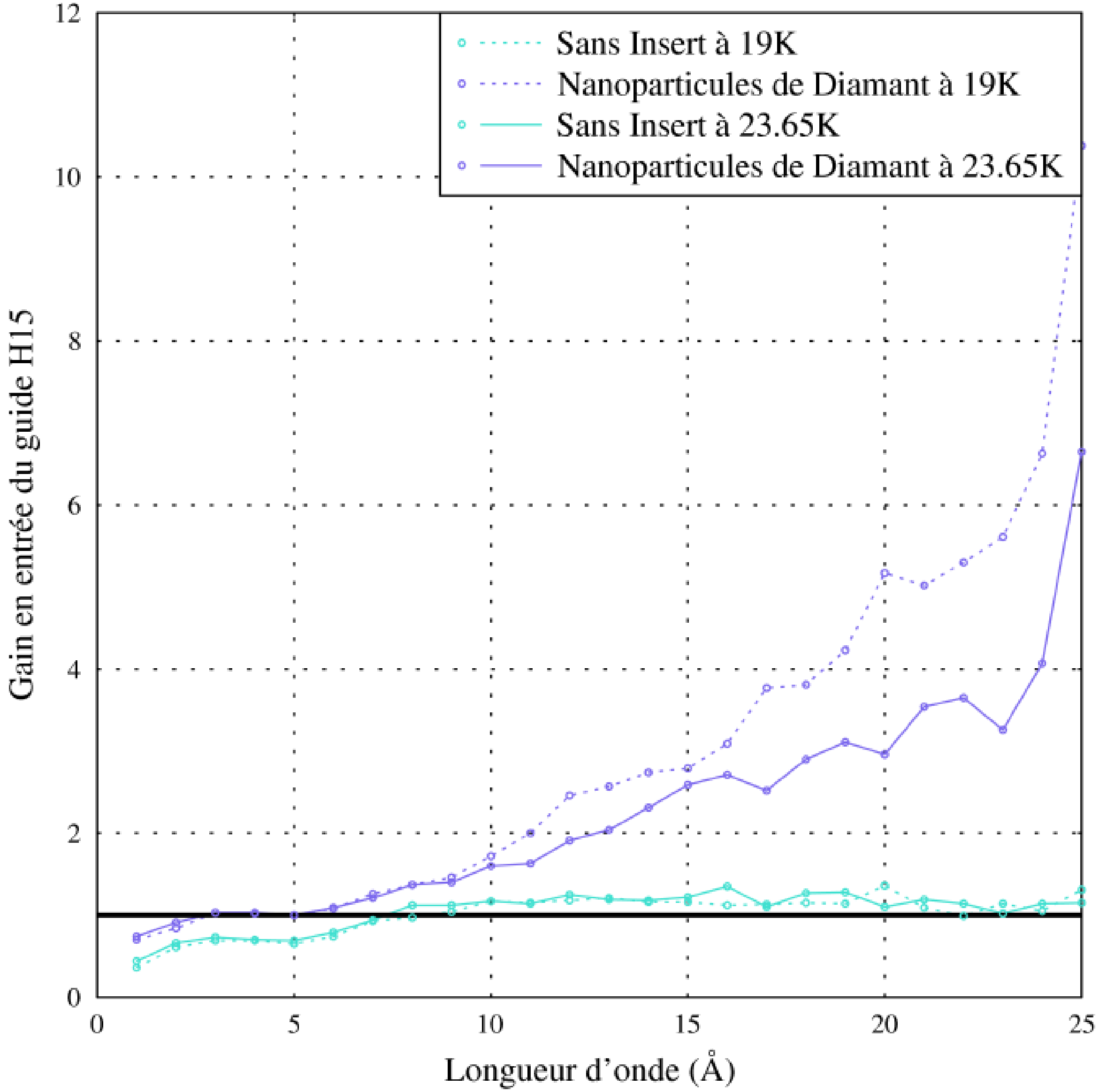
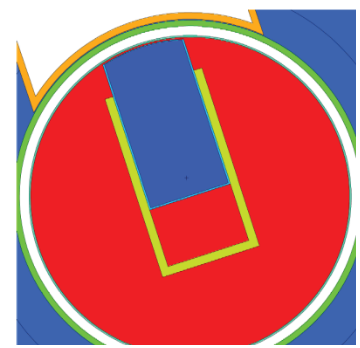


FIG. 1 – Coupe 3D du coeur du RHF.

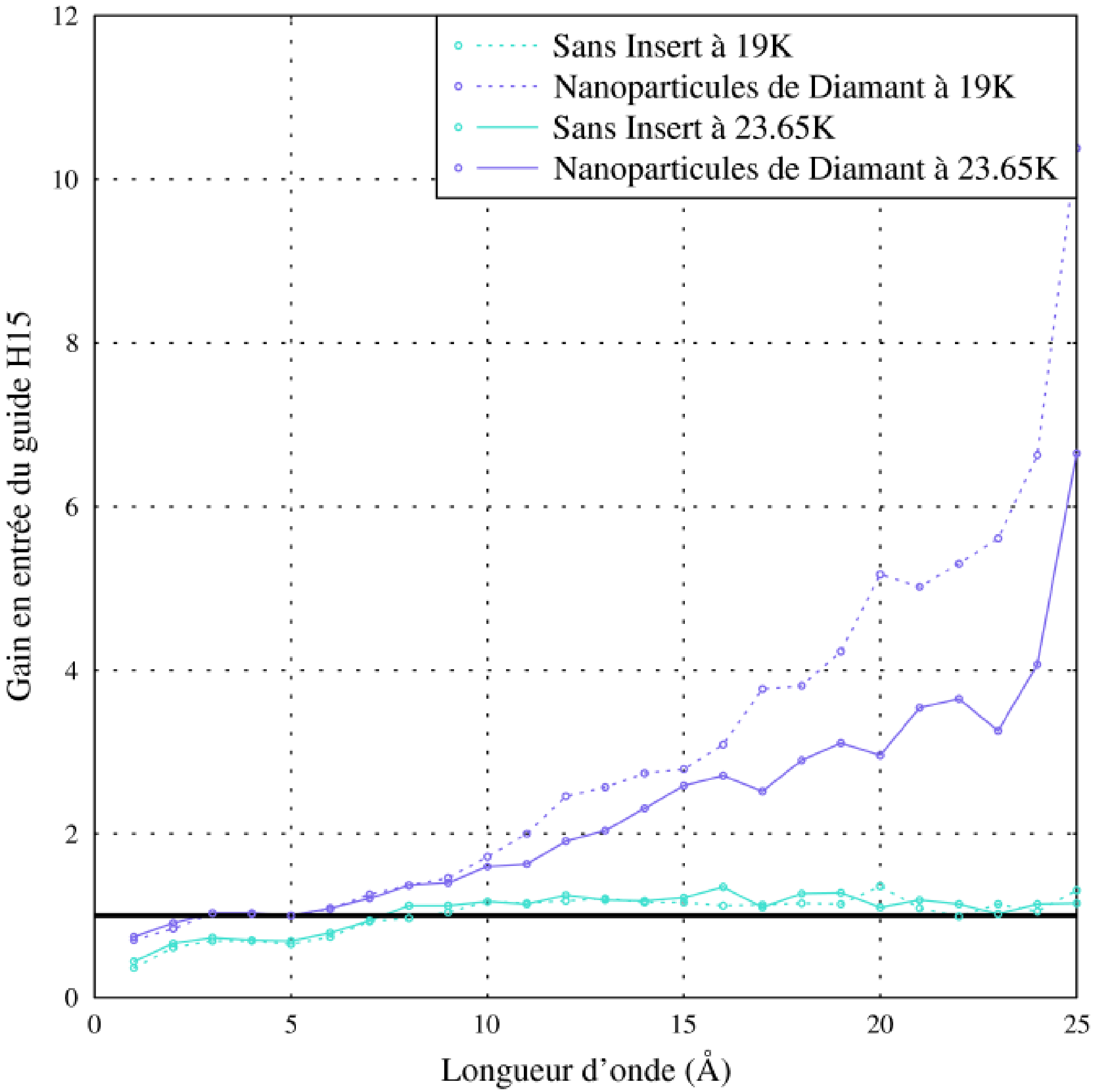
Possible applications
for sources of UCN, VCN and cold neutrons



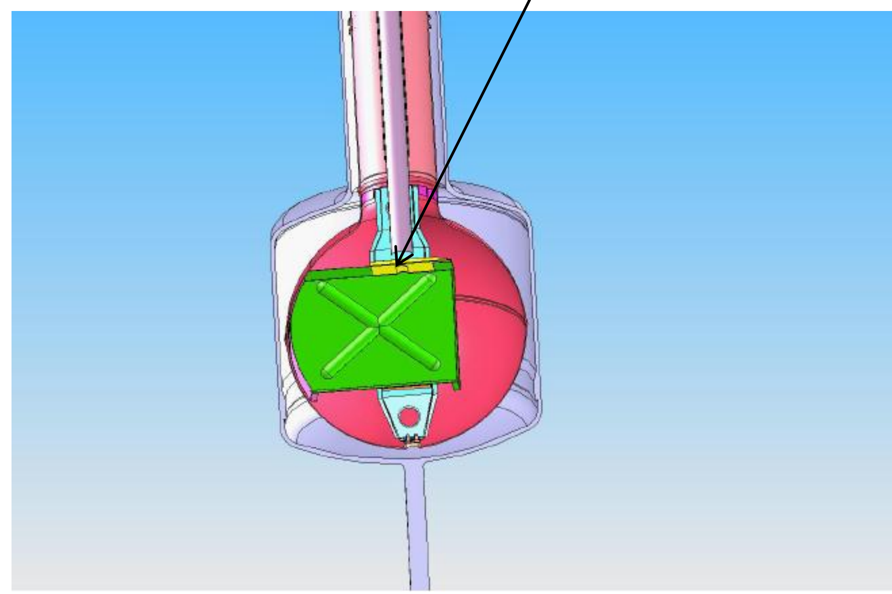
Y. CALZAVARA



Possible applications for sources of UCN, VCN and cold neutrons

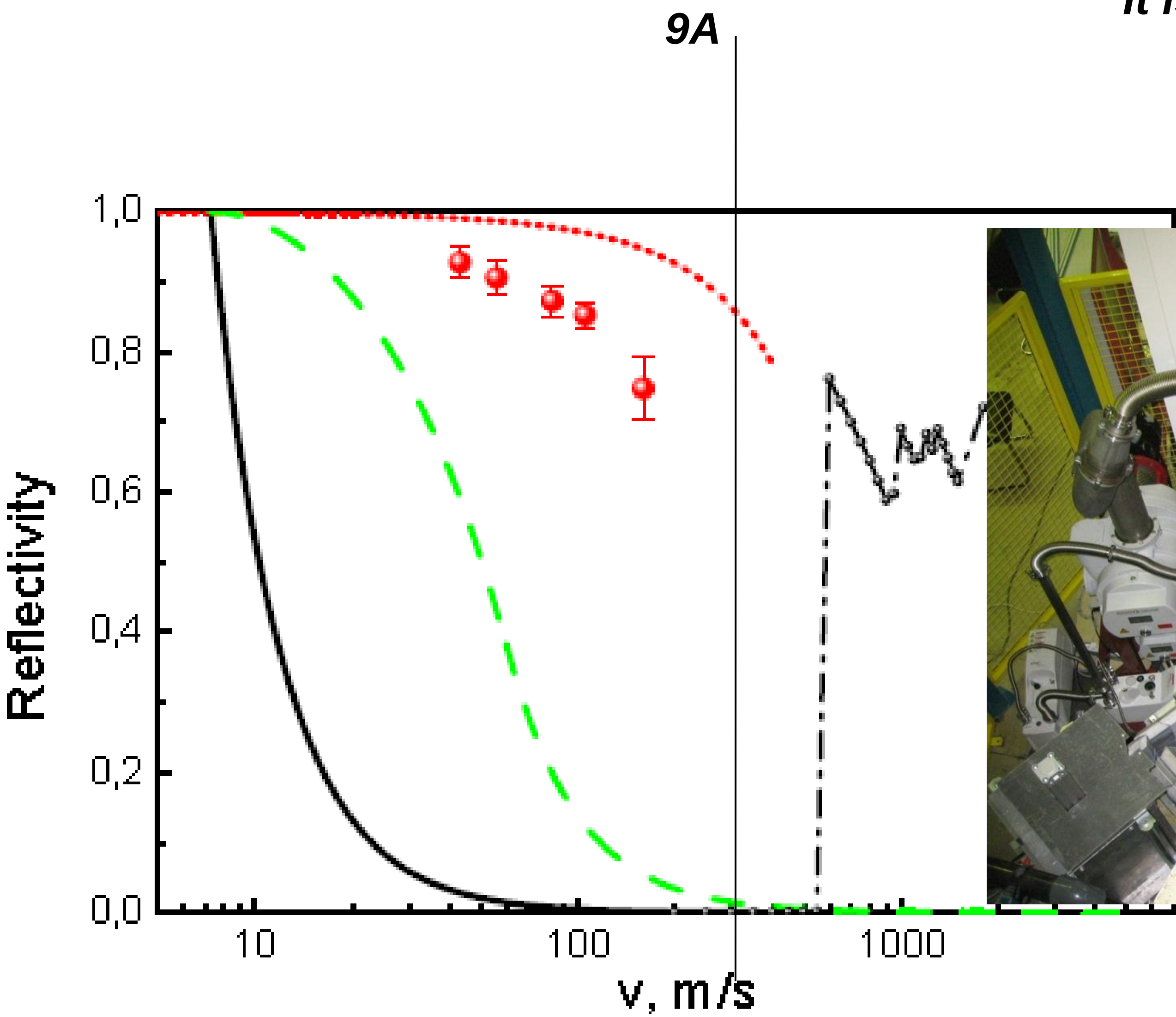


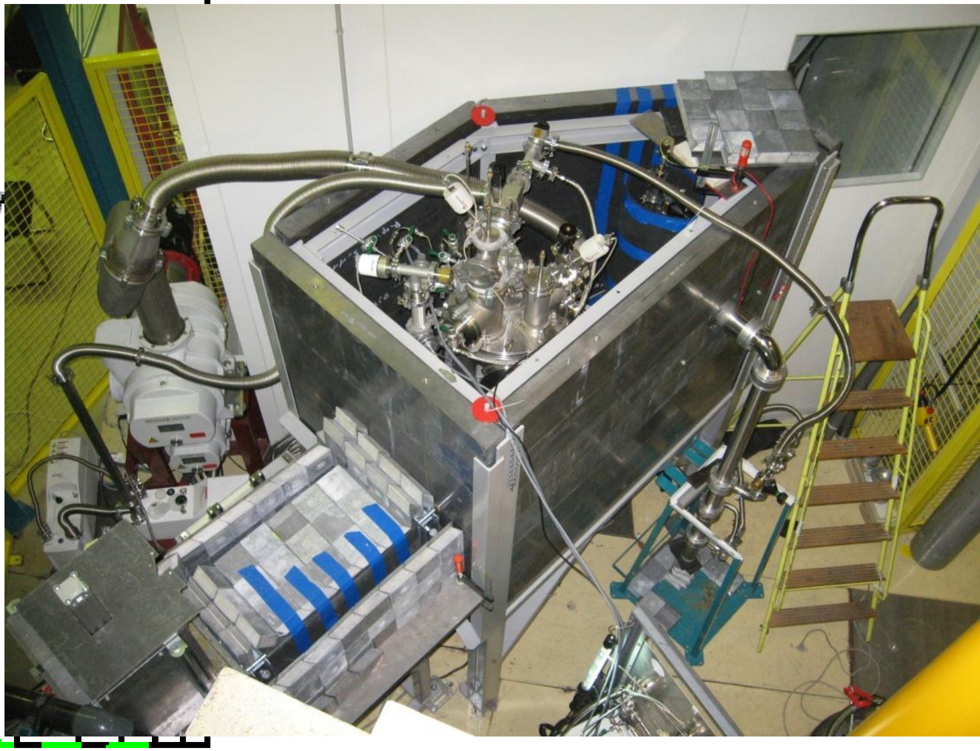
A huge potential gain factor in VCN (and UCN) fluxes if powders of nanoparticles are used for the vertical extraction, in particular if the temperature in a small zone inside the guide could be decreased



Possible applications for sources of UCN, VCN and cold neutrons

It is interesting to study if such a reflector could be used for 4He GRANIT UCN source





Possible applications
Intermediate conclusion

- *A large gain in neutron fluxes in the range 10-30 A and at larger wavelengths is possible using powders of diamond nanoparticles*
- *A detailed study is needed for any configuration, as the gain factor depends on many parameters, which should be considered simultaneously*
- *Some initial parts of super-mirror guides could be probably replaced by powders of diamond nanoparticles as they provide much higher resistance to radiation (this option has not yet been studied in detail)*

Behavior of nanoparticles in high radiation fluxes

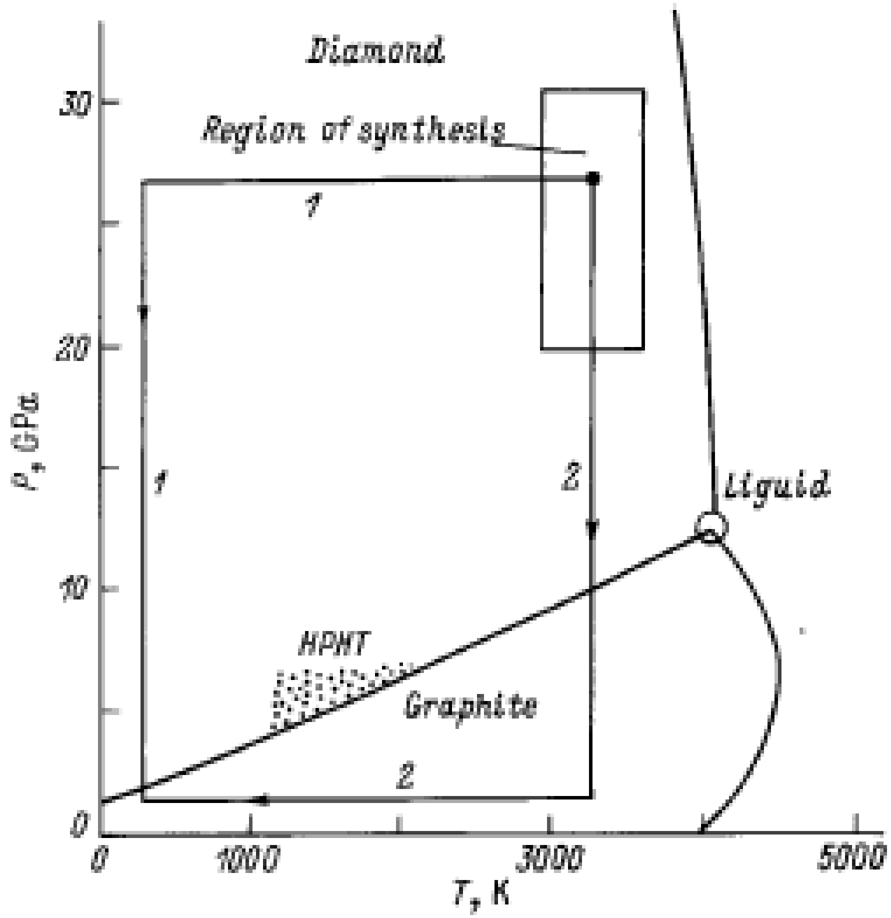


Рис. 1. Фазовая диаграмма углерода и кинетика охлаждения продуктов детонационного синтеза для двух идеализированных случаев: скорость охлаждения много больше (1) и много меньше (2) скорости падения давления.

Behavior of nanoparticles in high radiation fluxes

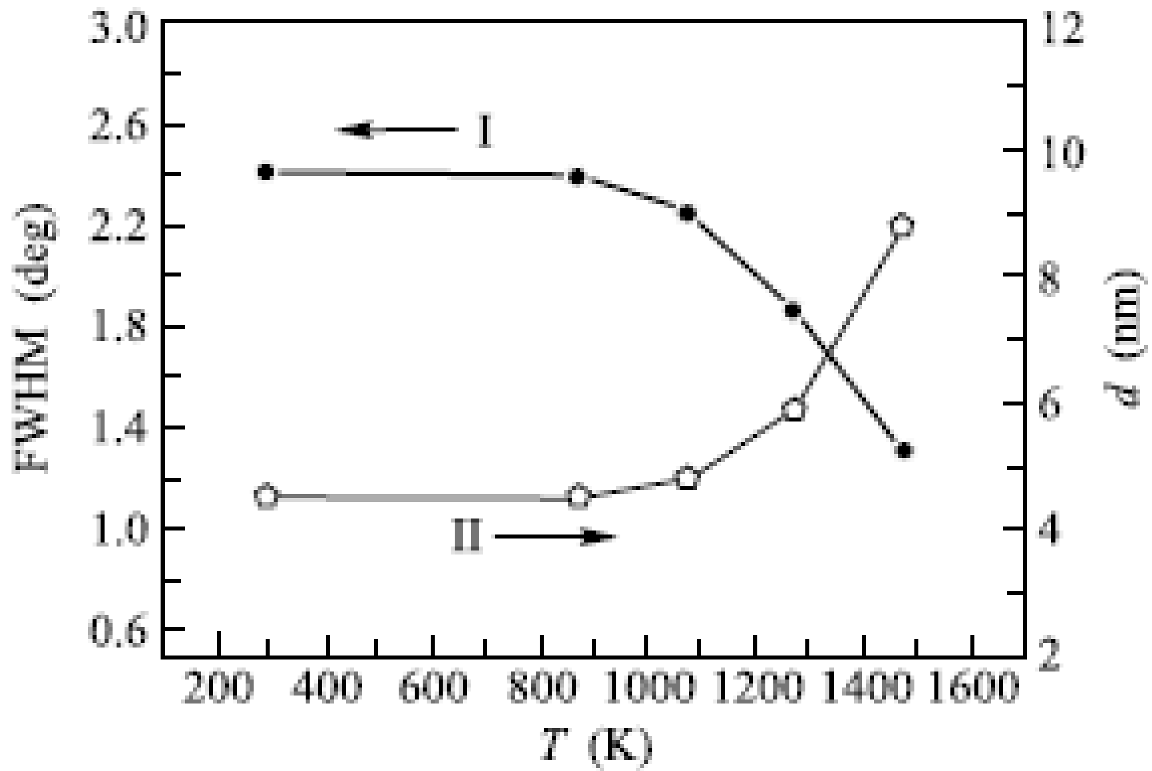


Рис.2. Температурные зависимости ширины дифракционного пика (111) алмаза (I) и среднего размера алмазных частиц (II), полученных в результате обработки исходного порошка НА со средним размером частиц 4.5 нм при 8 ГПа

THE CONCLUSION

- *Powders of diamond nanoparticles provide the first efficient reflector for very cold neutrons*
- *Powders of diamond nanoparticles provide efficient quasi-specular reflection of cold neutrons (up to the Bragg wavelength)*
- *Such powders could provide large gain in fluxes of slow neutrons in various configurations*
- *Each particular case has to be optimized driven by the needs of respective instruments/applications*
- *Behavior of diamond nanoparticles in high radiation fluxes is not well known and should be studied experimentally before their any application*
- *The calculated gain factors in low radiation fluxes could be guarantied today*

THE CONCLUSION