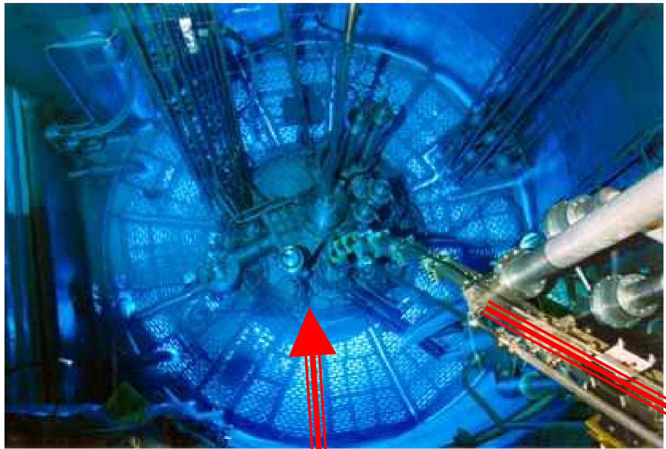
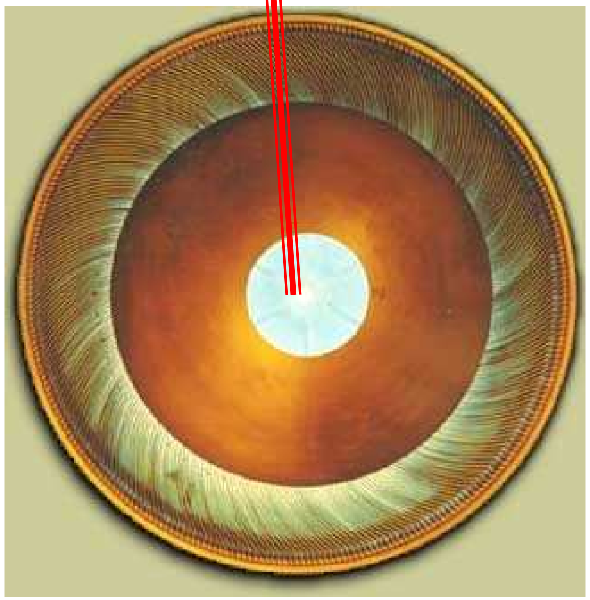
High-flux ILL reactor





NEUTRONS FOR SCIENCE

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

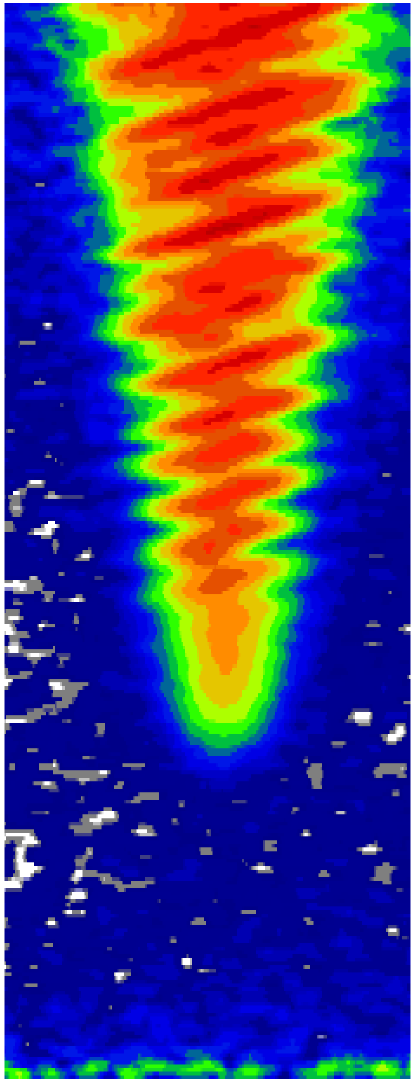
Granit

Gravitational Neutron Induced Transitions

1. Gravitational quantum states of neutrons

2. GRANIT project

3. Centrifugal quantum states of neutrons



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§

* *Institute Laue-Langevin, 6 rue Jules Horowitz, Grenoble F-38042, France*
† *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

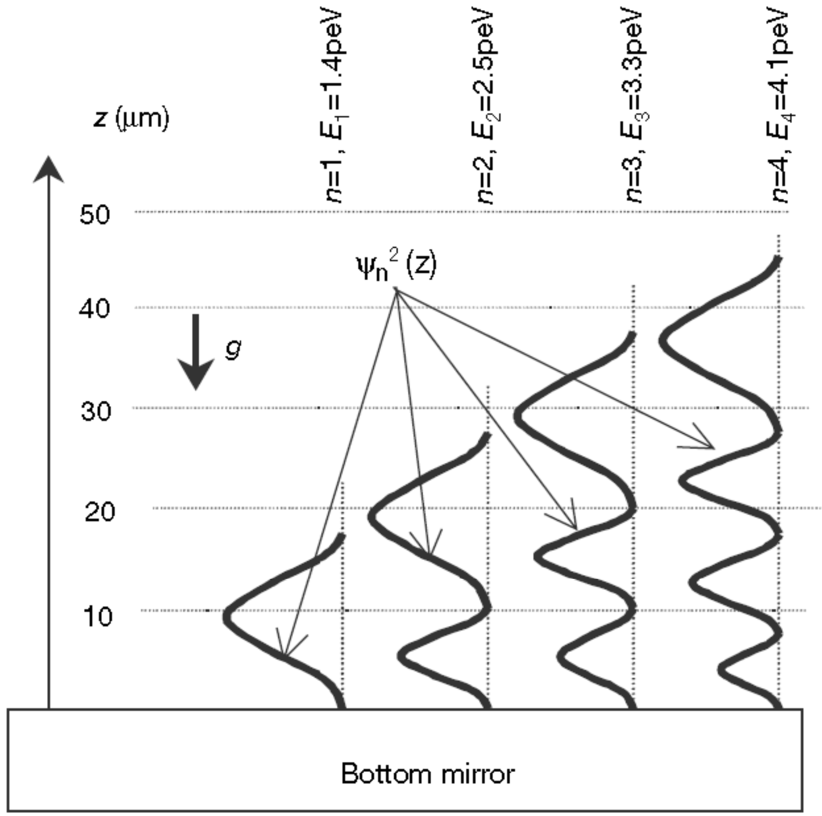
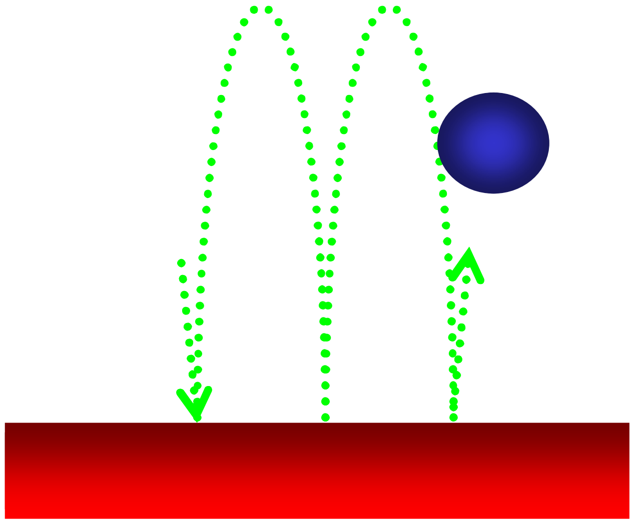


Figure 1 Wavefunctions of the quantum states of neutrons in the potential well formed by the Earth's gravitational field and the horizontal mirror. The probability of finding neutrons at height z, corresponding to the nth quantum state, is proportional to the square of the neutron wavefunction $\psi_n^2(z)$.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

Which quantum system?



Neutron avobe mirror in gravity field

(mirror represents nearly infinitely high and sharp potetial step)

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

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

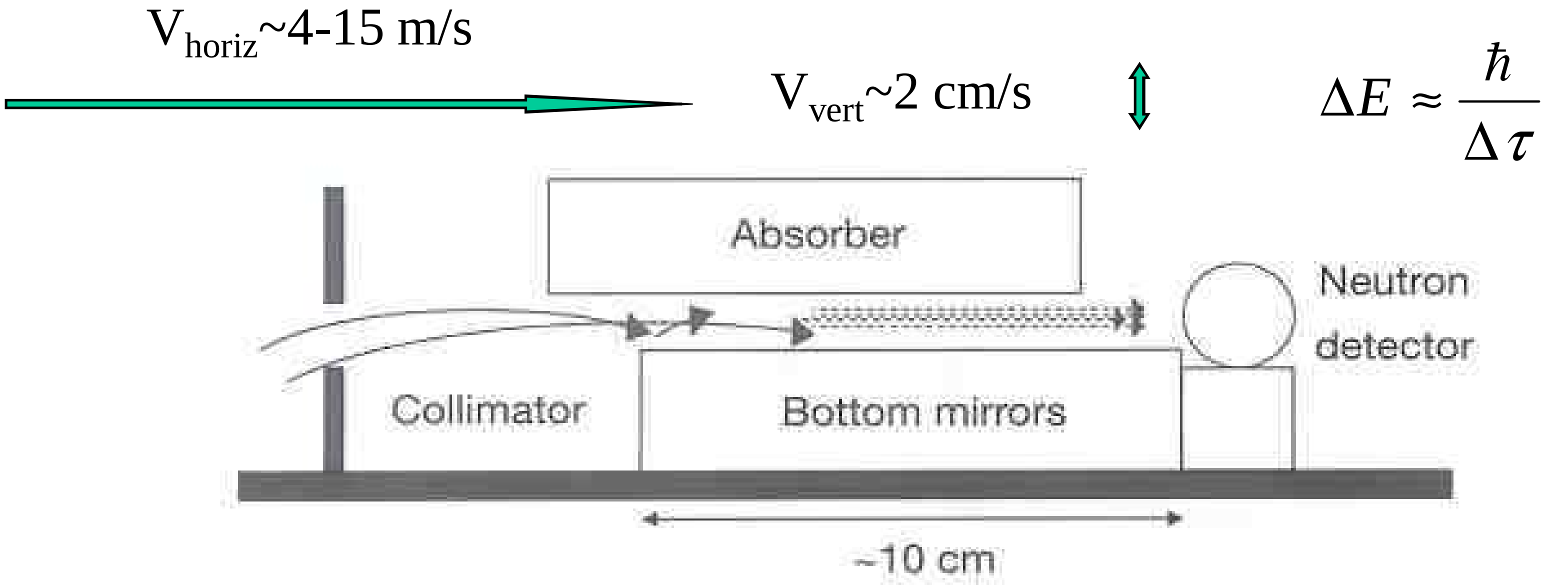
3) *Small mass* $\left(\Delta v \cdot \Delta x \approx \frac{\hbar}{m}\right)$

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

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



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

$$\xi >> 1$$

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

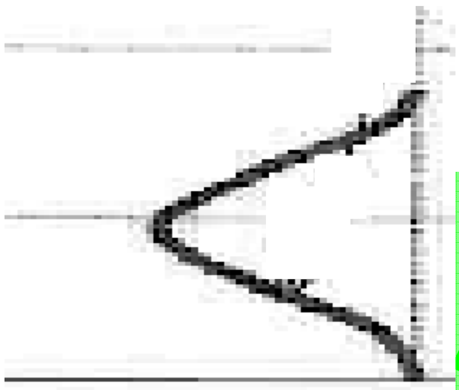
$$D(\xi) \approx Exp[-\frac{4}{3} \cdot \xi^{\frac{3}{2}}],$$

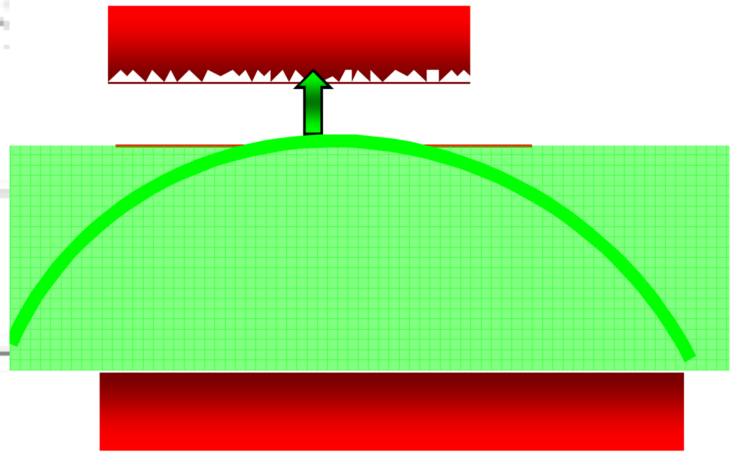
$$P_n(\xi) = Exp(-\Gamma_n(\xi) \cdot \tau)$$

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

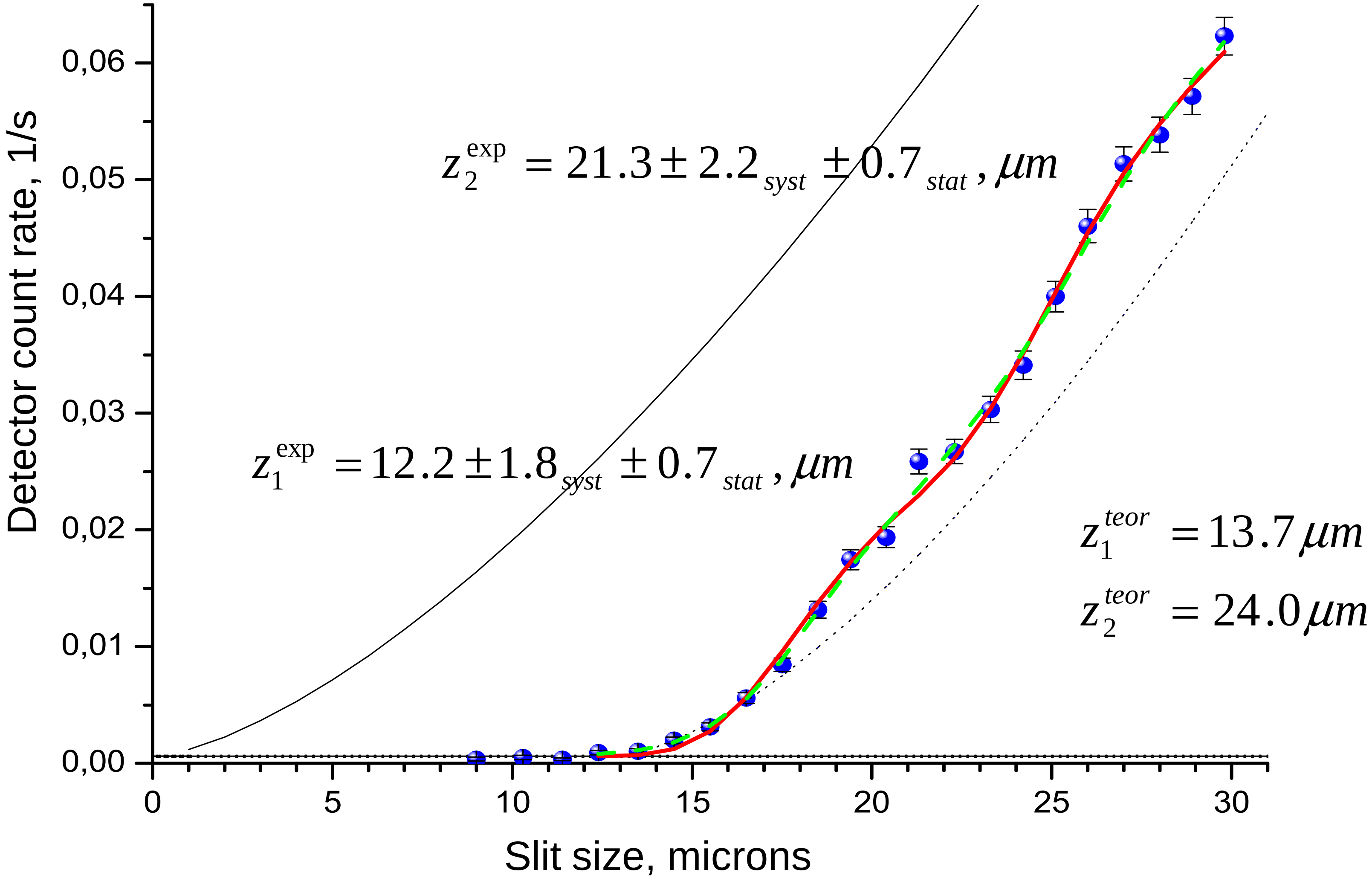
$$D(\xi) = \begin{cases} 1, \xi < 0 \\ A_n \cdot Exp[-\frac{4}{3} \cdot \xi^{\frac{3}{2}}], \xi \end{cases}$$

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



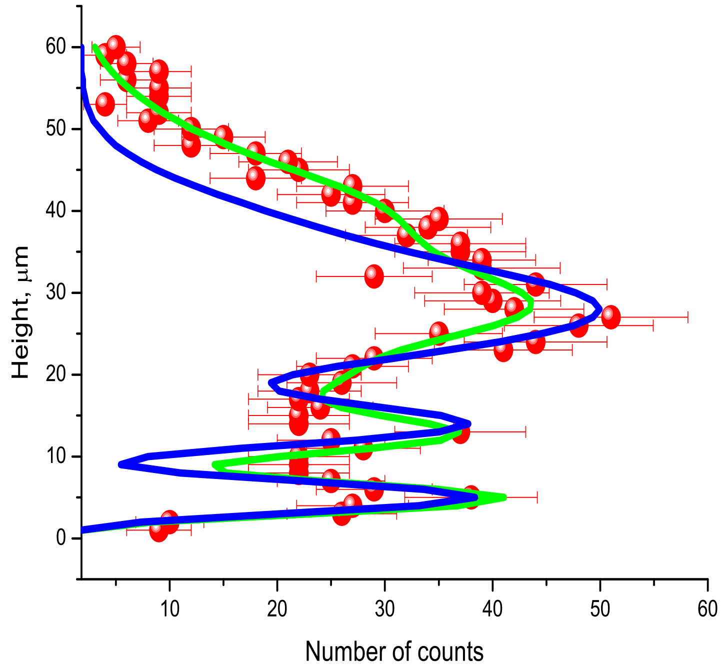


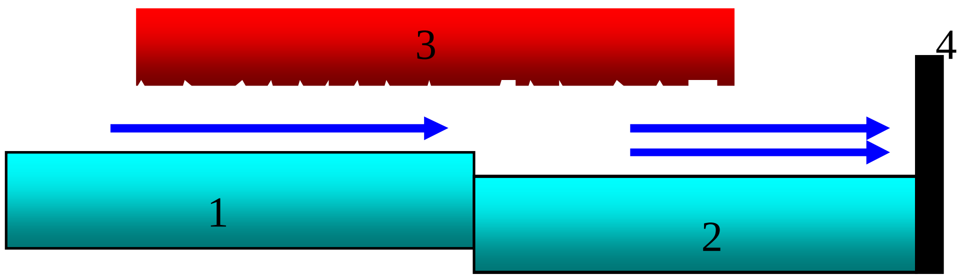
« Integral » method; soft spectrum



« Differential » method, position-sensitive detectors

A method to increase the spatial variation of neutron density





« Differential » method, position-sensitive detectors

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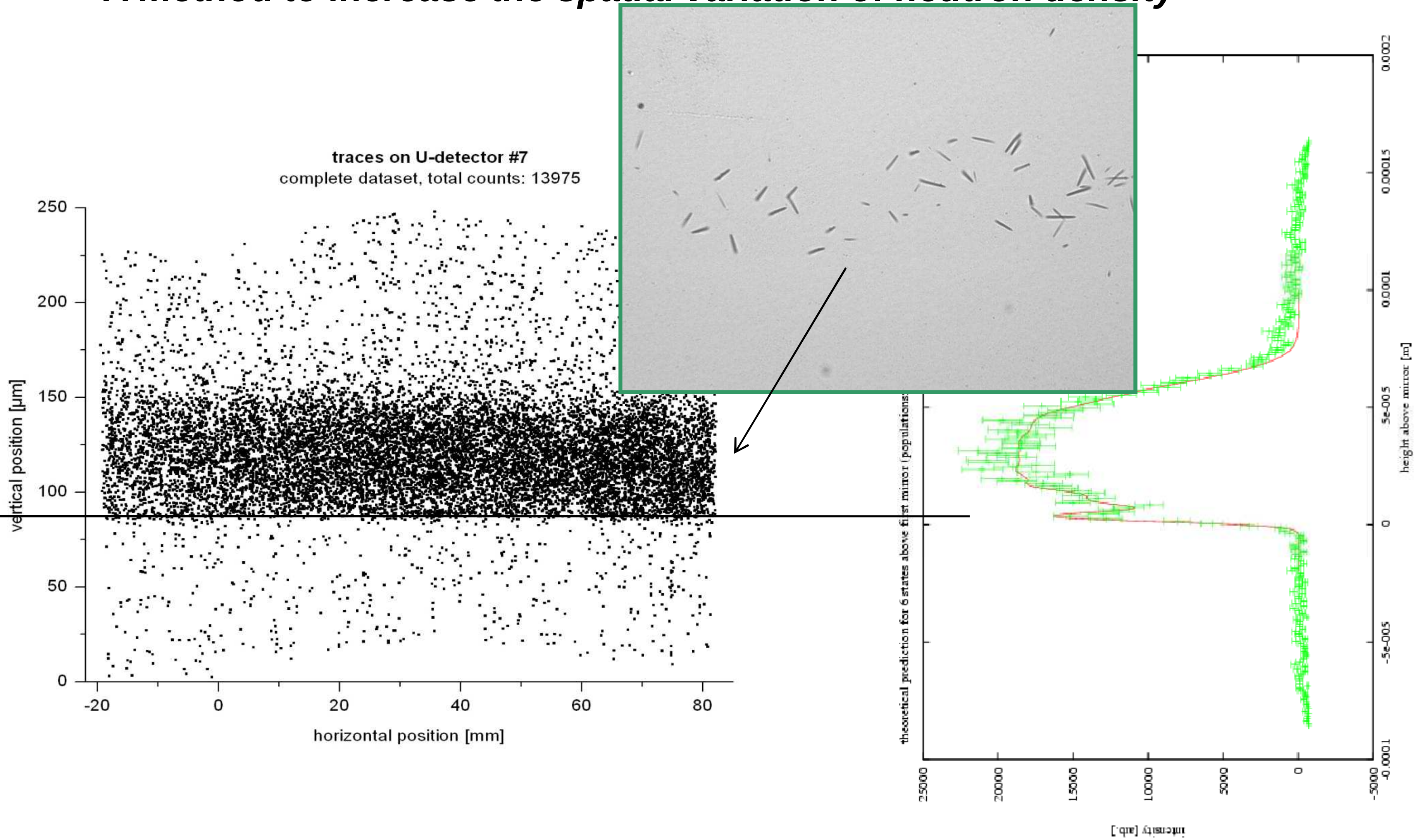


Transitions between gravitational quantum states

Remember: flow-through mode; modest energy resolution

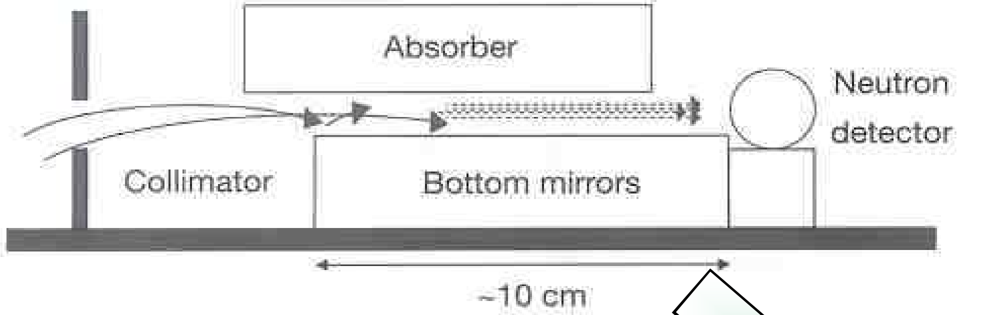


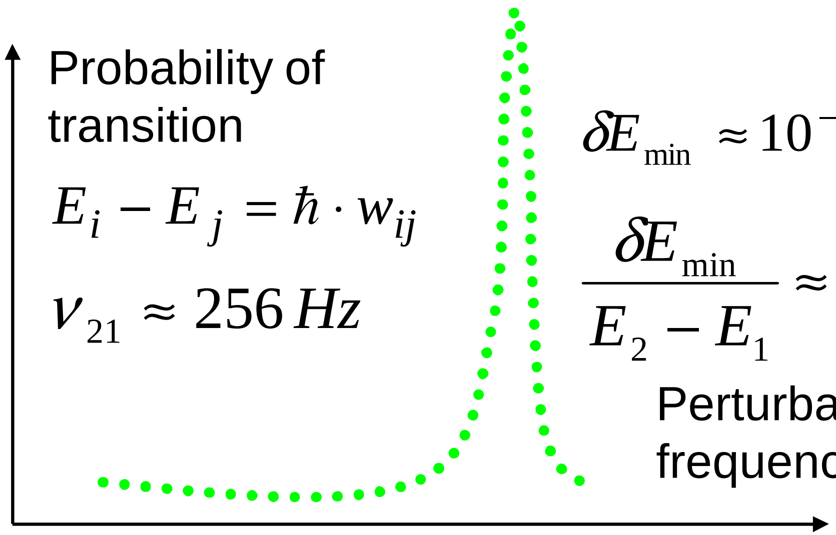
Figure 2 Layout of the experiment. The limitation of the vertical velocity component depends on the relative position of the absorber and mirror. To limit the horizontal velocity component we use an additional entry collimator. The relative height and size of the entry collimator can be adjusted.

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)



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

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

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

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

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

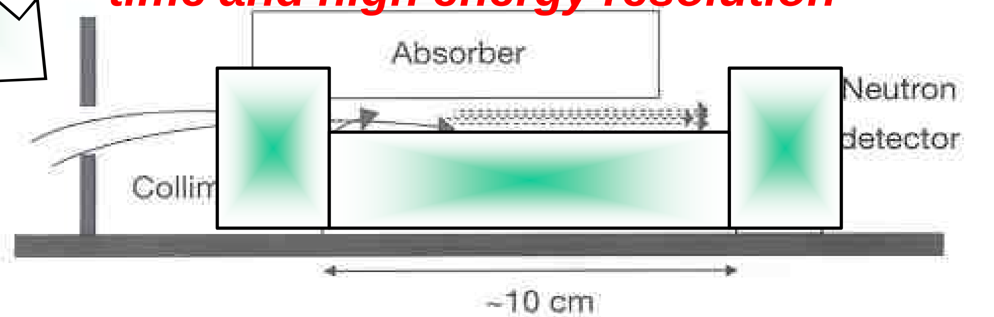
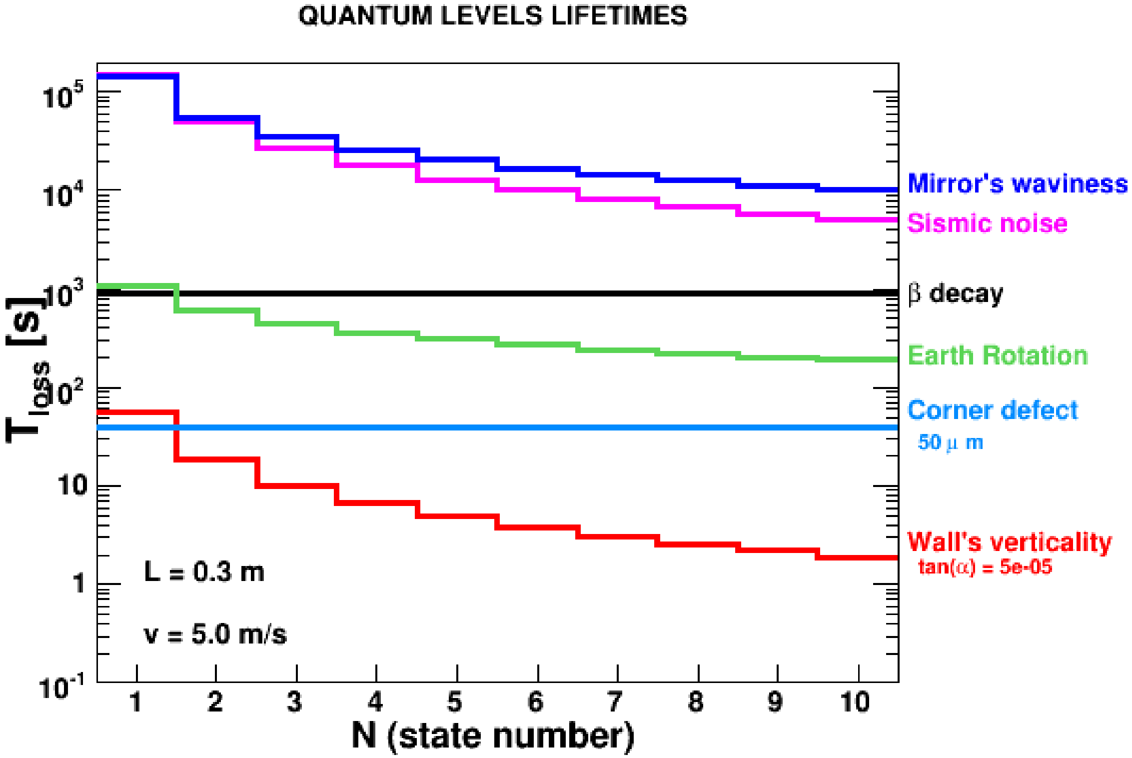
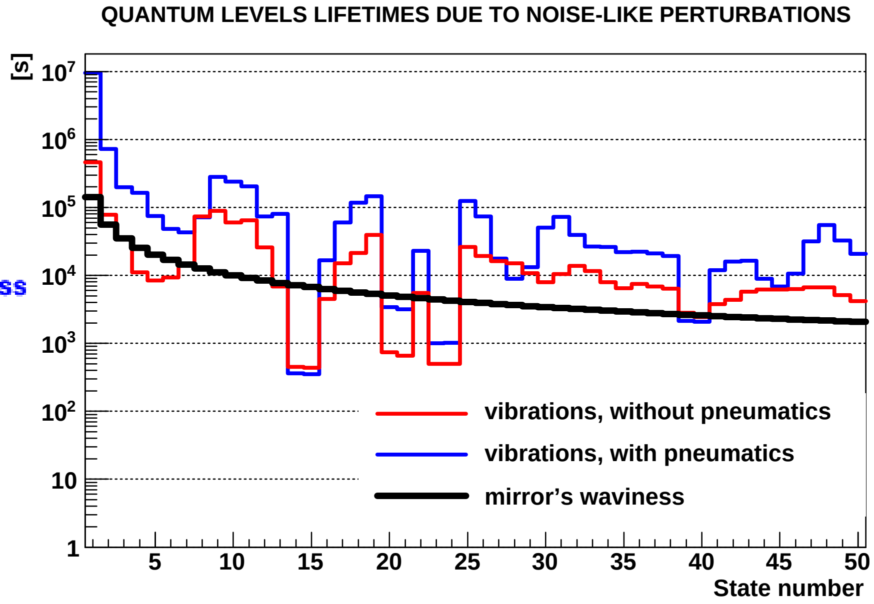
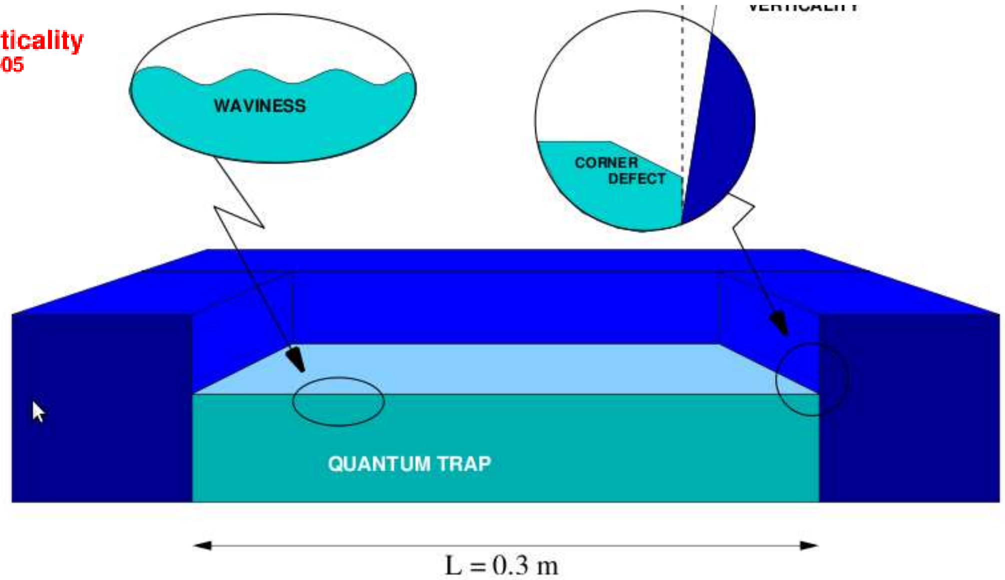


Figure 2 Layout of the experiment. The limitation of the vertical velocity component depends on the relative position of the absorber and mirror. To limit the horizontal velocity component we use an additional entry collimator. The relative height and size of the entry collimator can be adjusted.

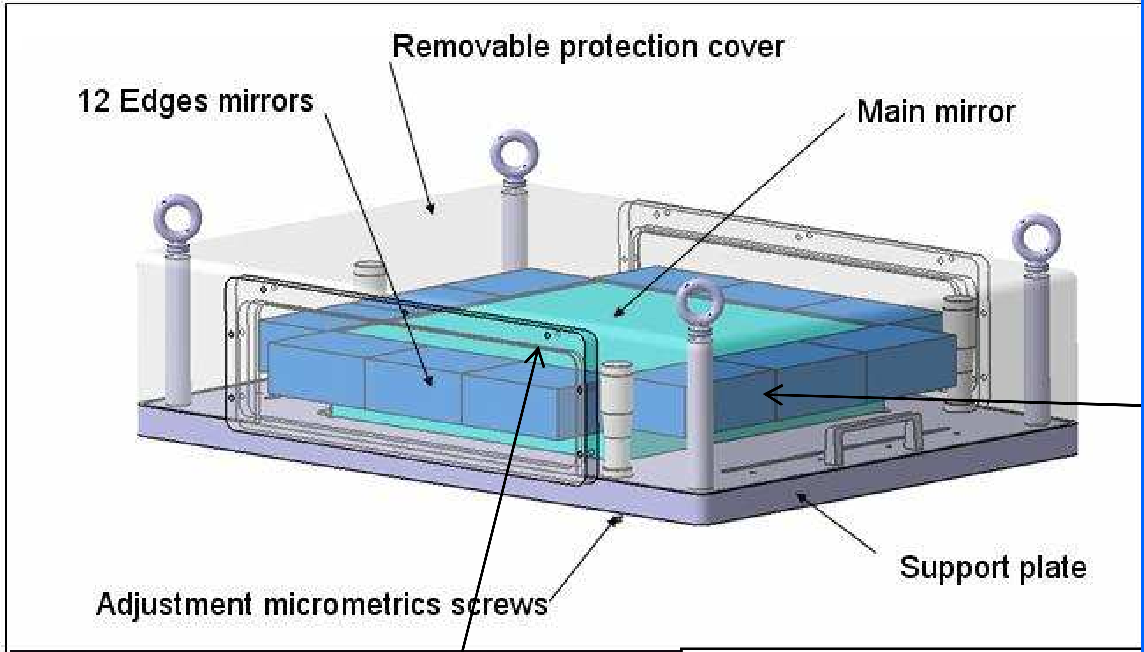
Storage of UCN in gravitational quantum states

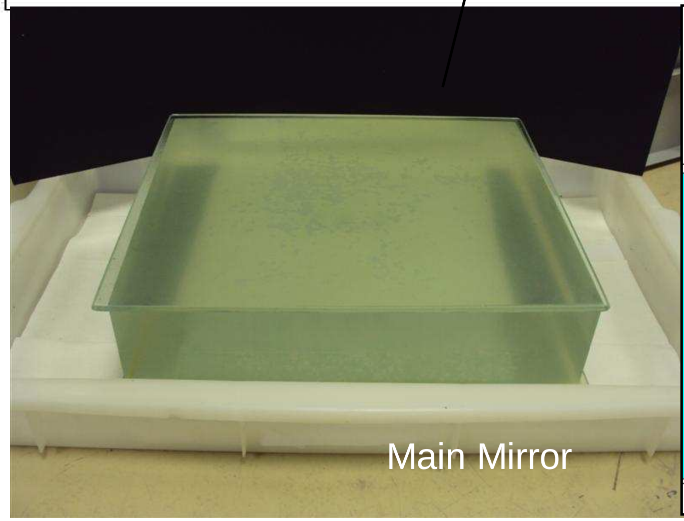


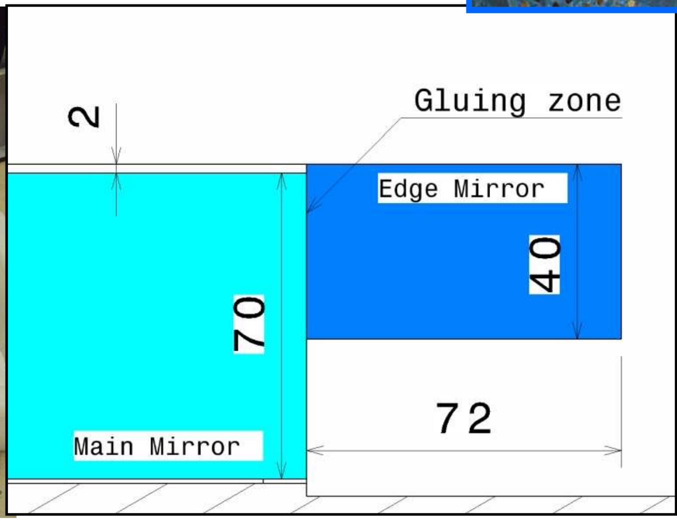


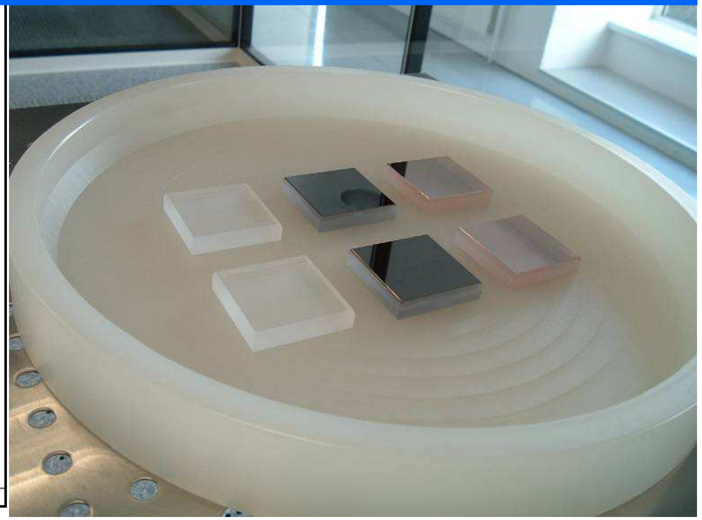


Transitions between gravitational quantum states
Quantum trap 30cm by 30cm; Height of edges 0.5mm

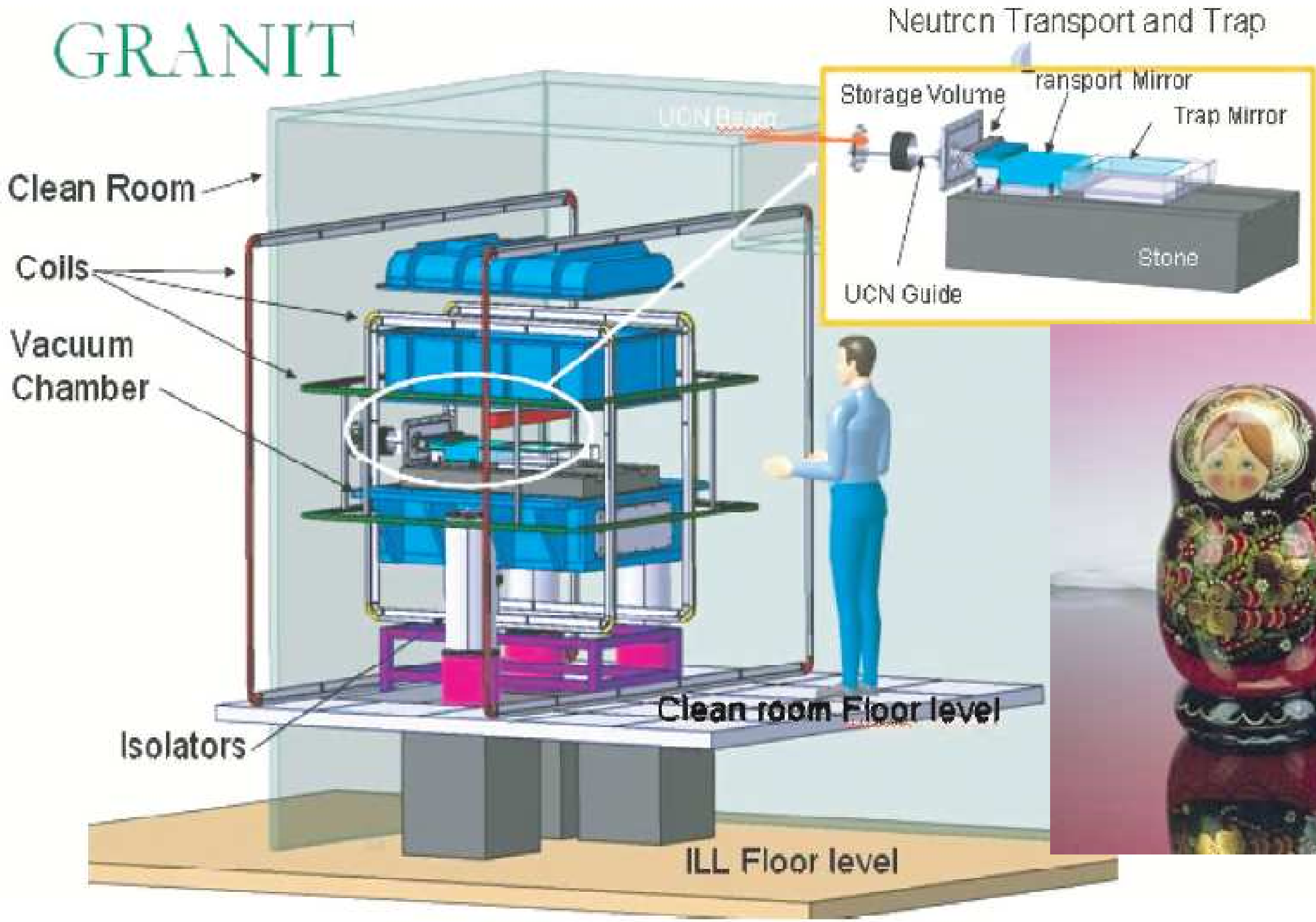






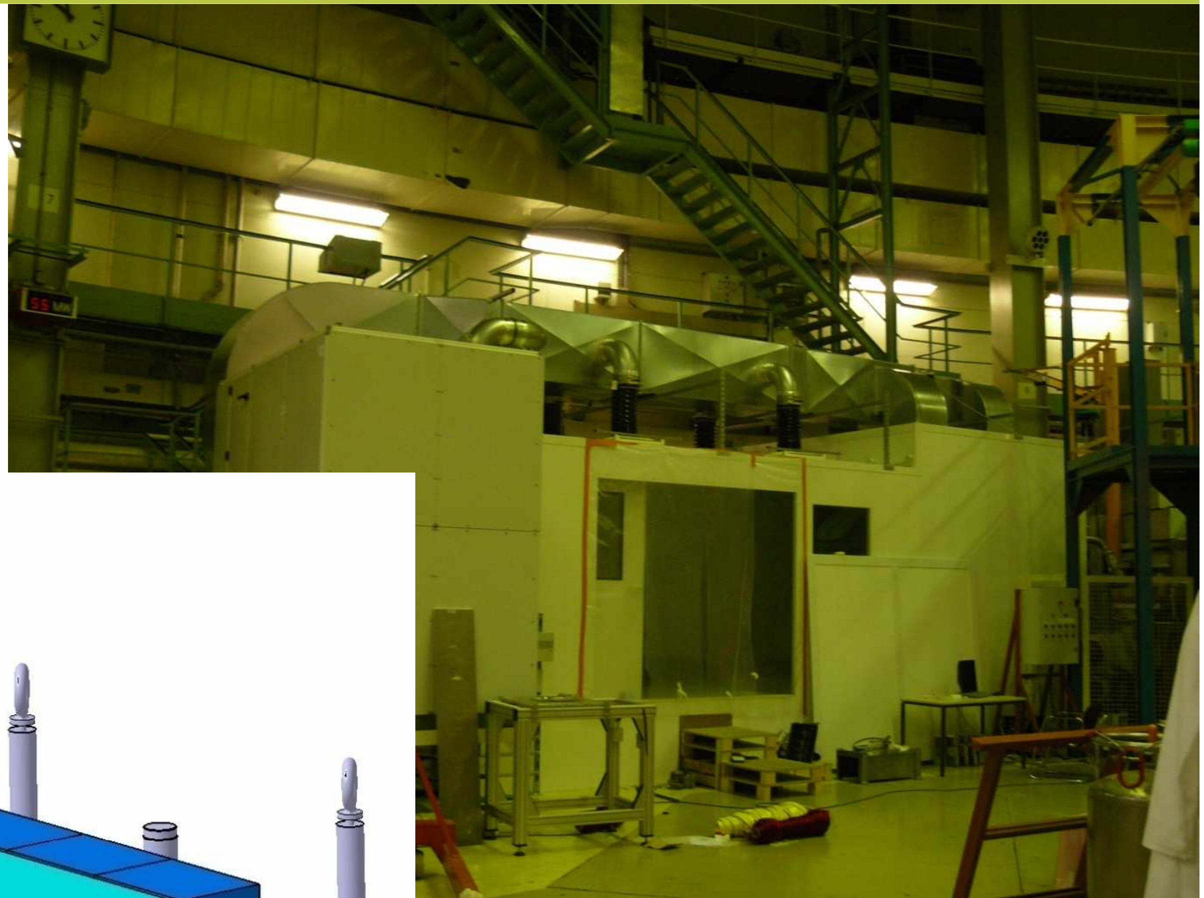


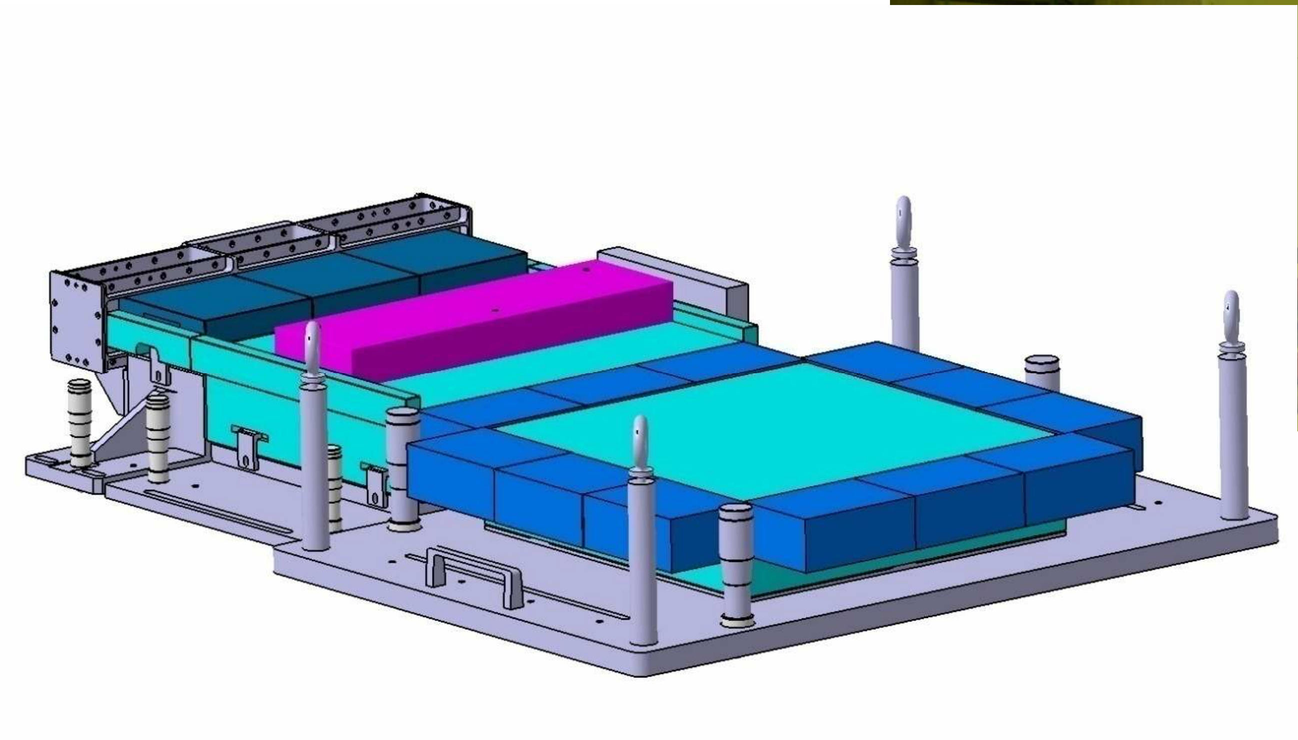
GRANIT
Assembling the spectrometer



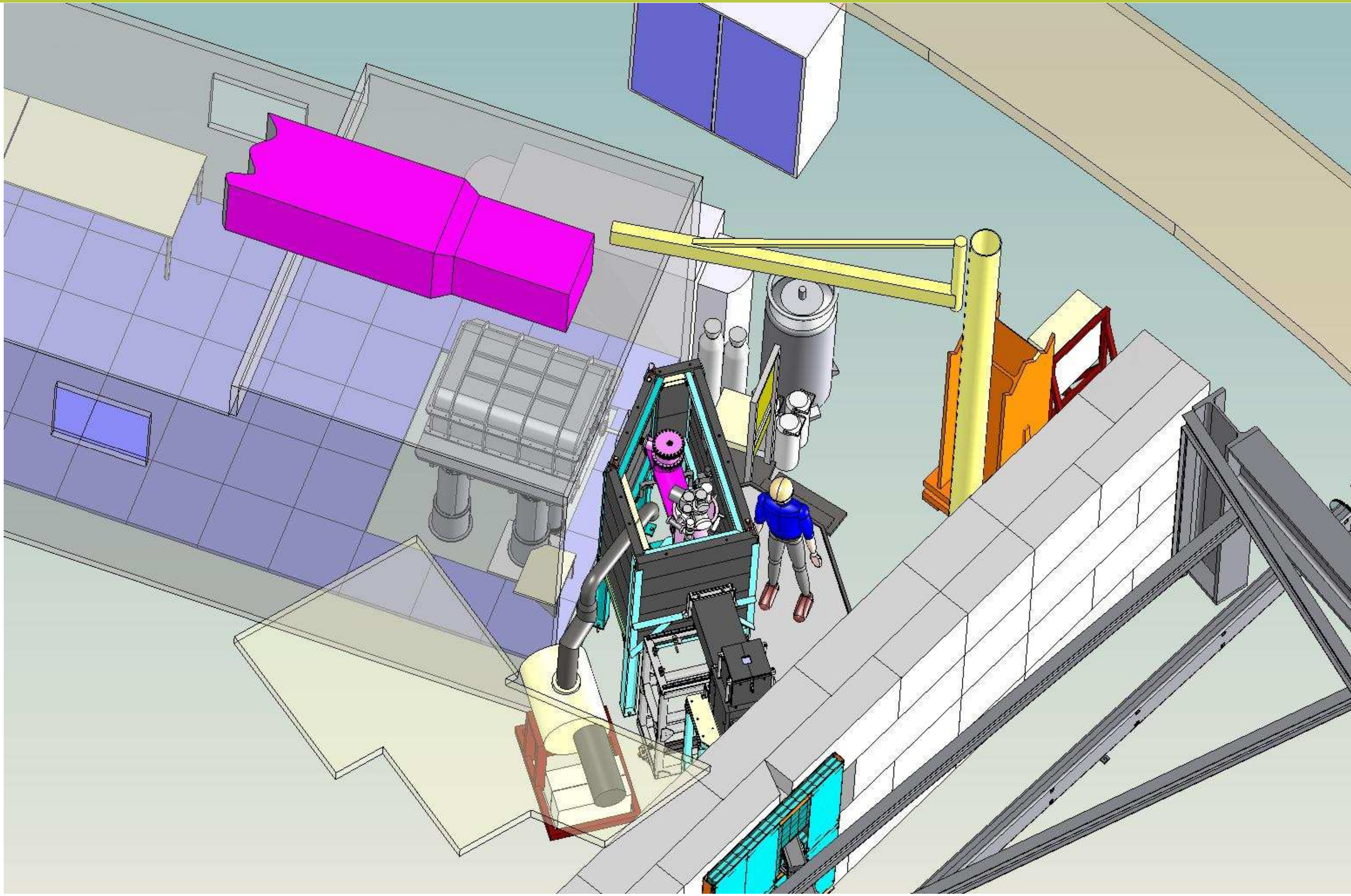
GRANIT

Extraction, transport, and storage mirrors; Clean room





Installation of GRANIT spectrometer at the level C at ILL



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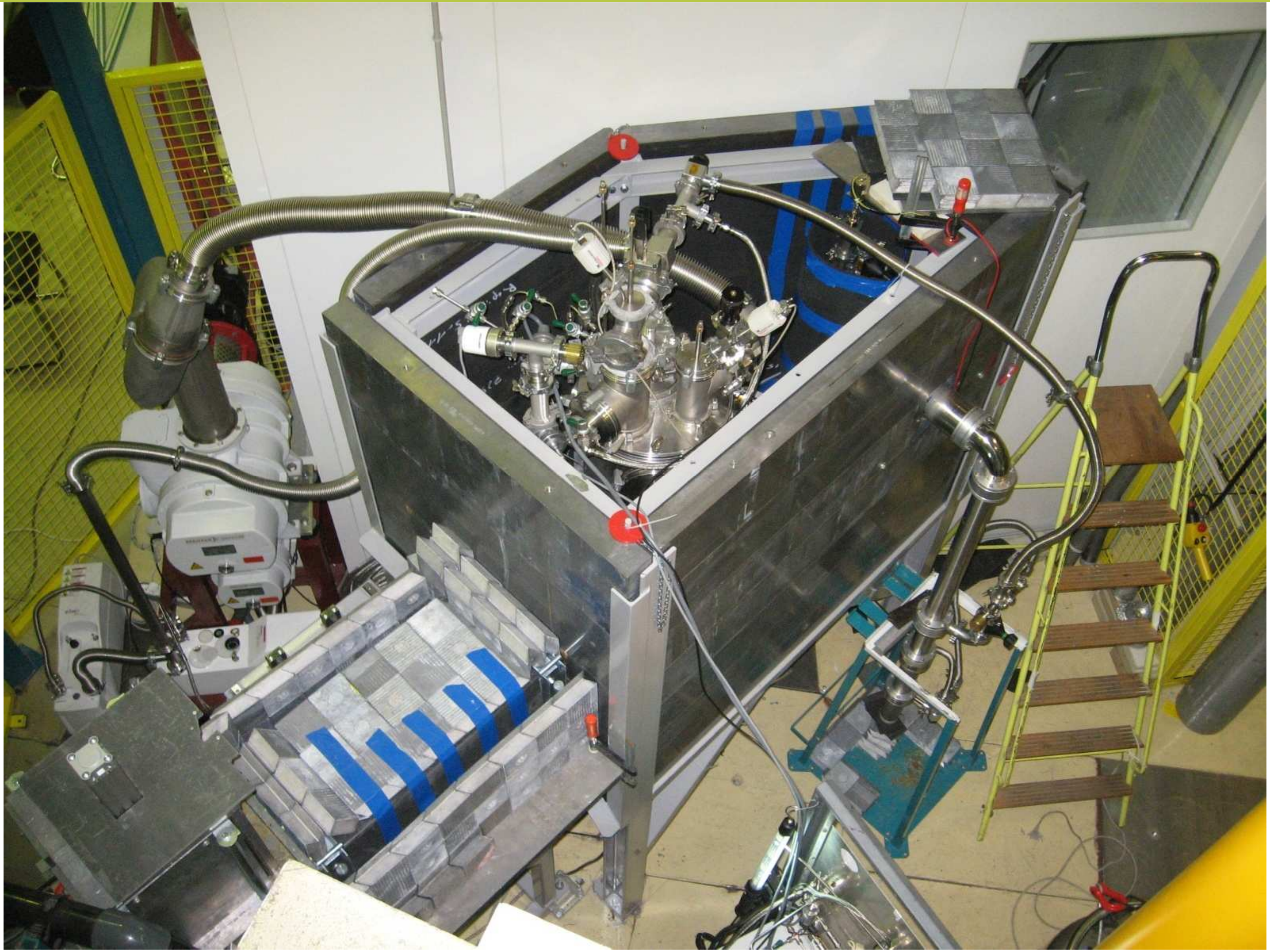
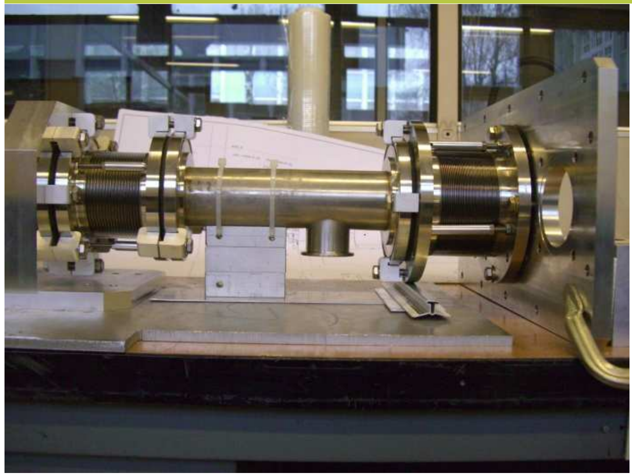
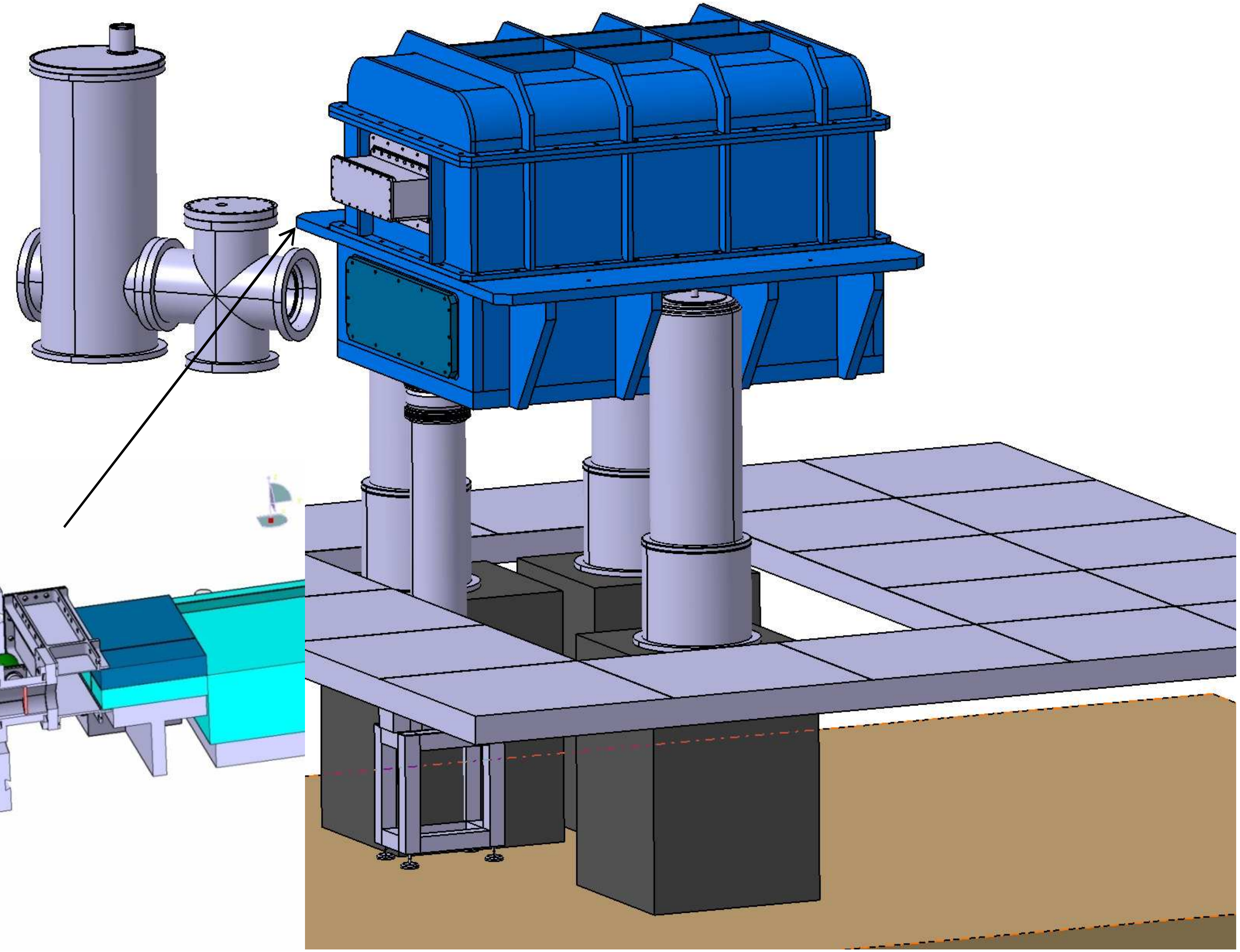
V.V. Nesvizhevsky

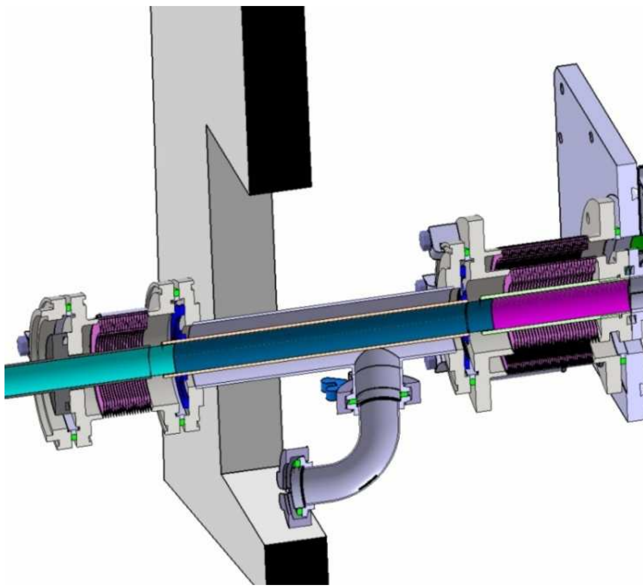
Installation of GRANIT spectrometer at the level C at ILL



GRANIT
and UCN source

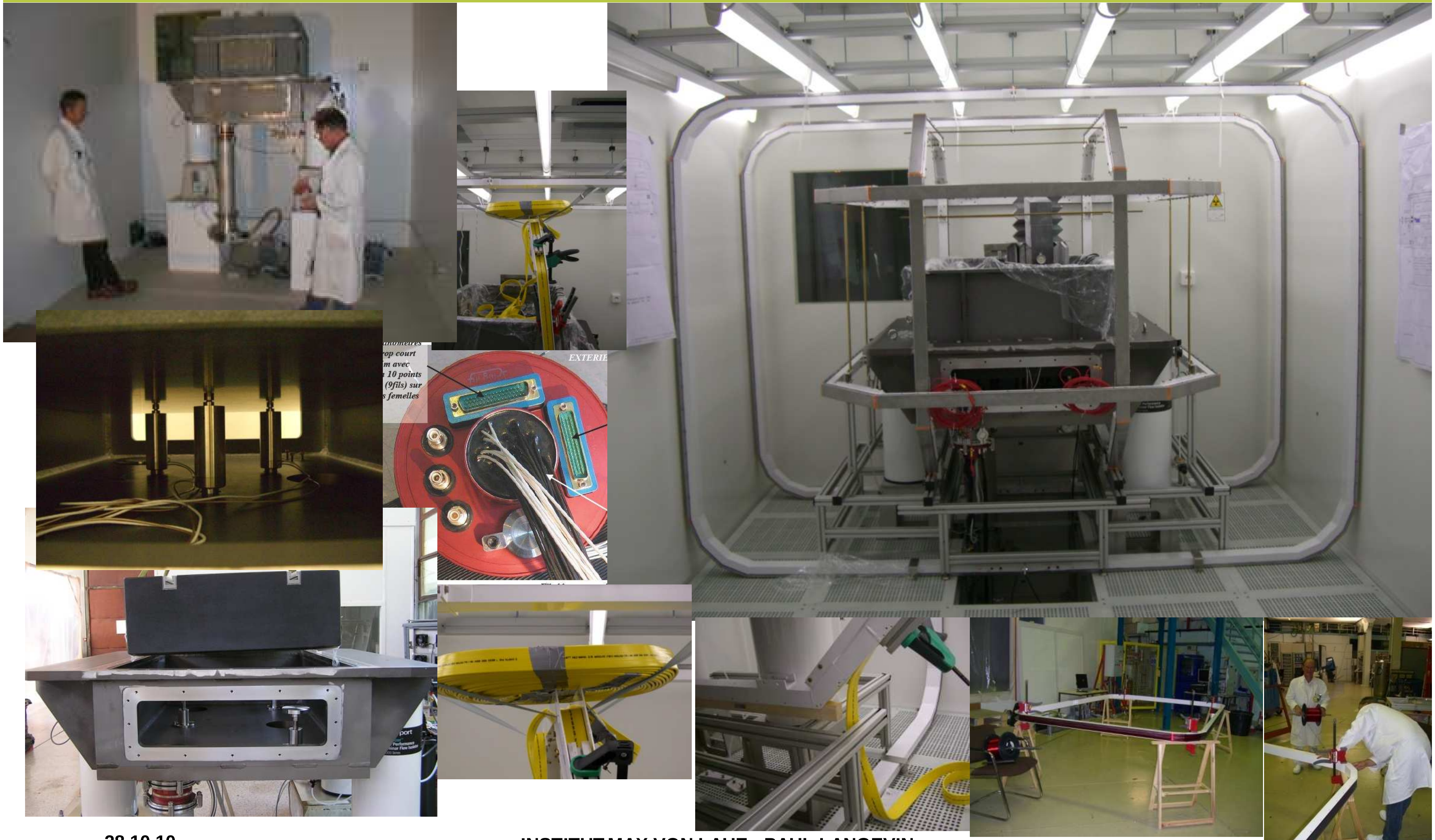




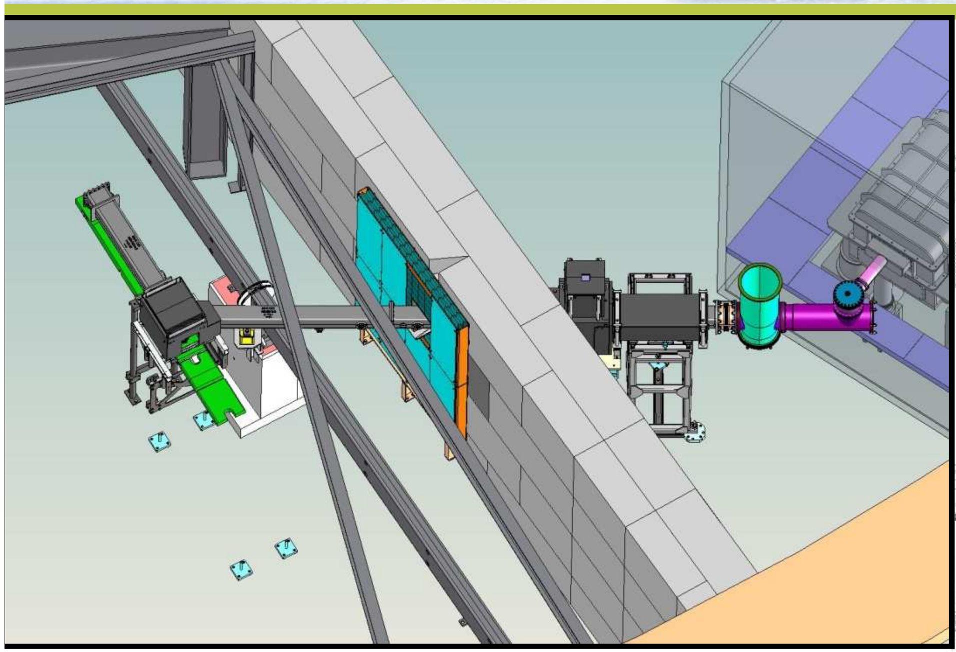


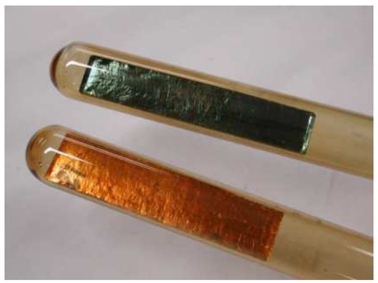
NEUTRONS FOR SCIENCE

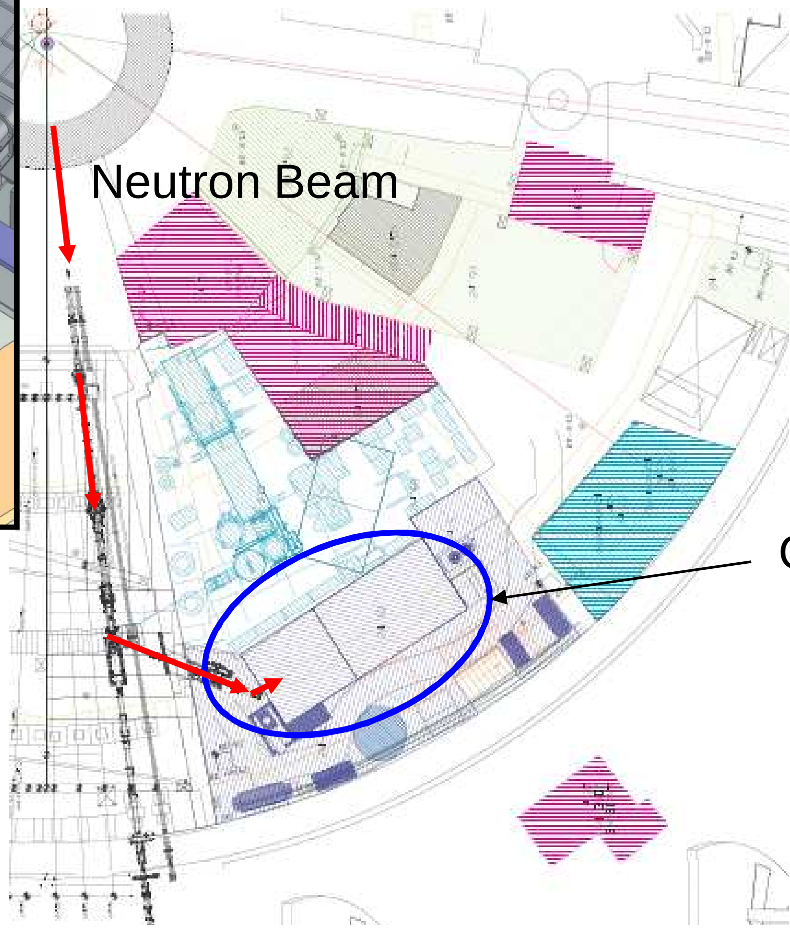
GRANIT
Control of magnetic fields, vacuum chamber



Installation of GRANIT spectrometer at the level C at ILL

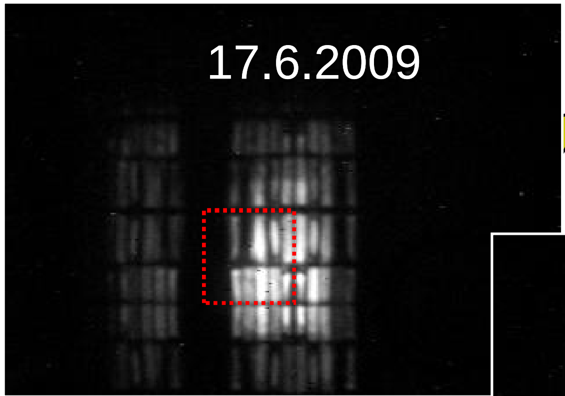






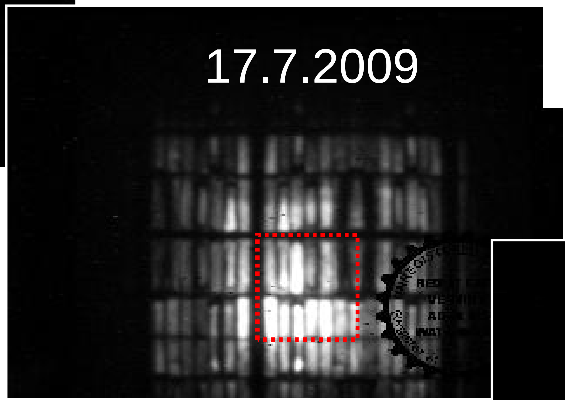
Located in the ILL reactor at level C

Installation of GRANIT spectrometer at the level C at ILL

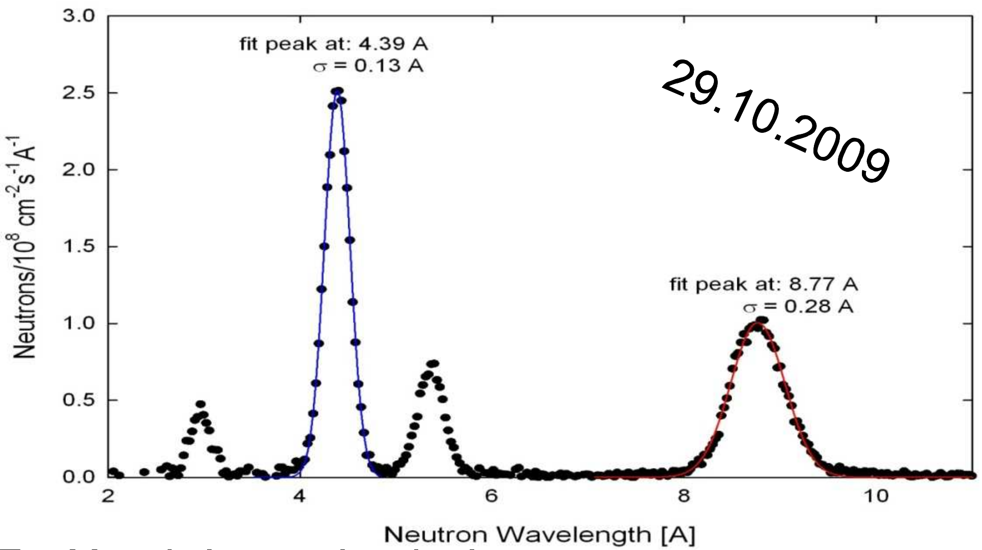


3.1×10^8 n $cm^{-2}s^{-1}$

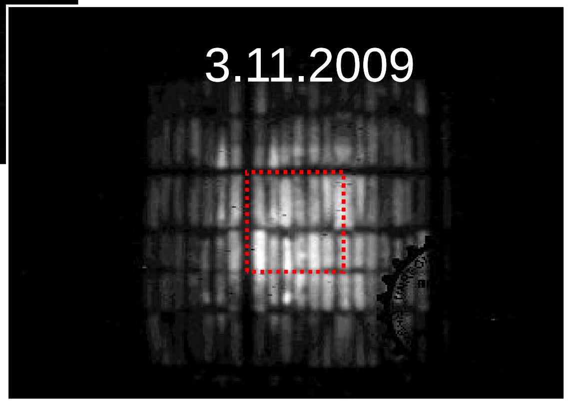
Monochromator turned



5.9×10^8 n $cm^{-2}s^{-1}$



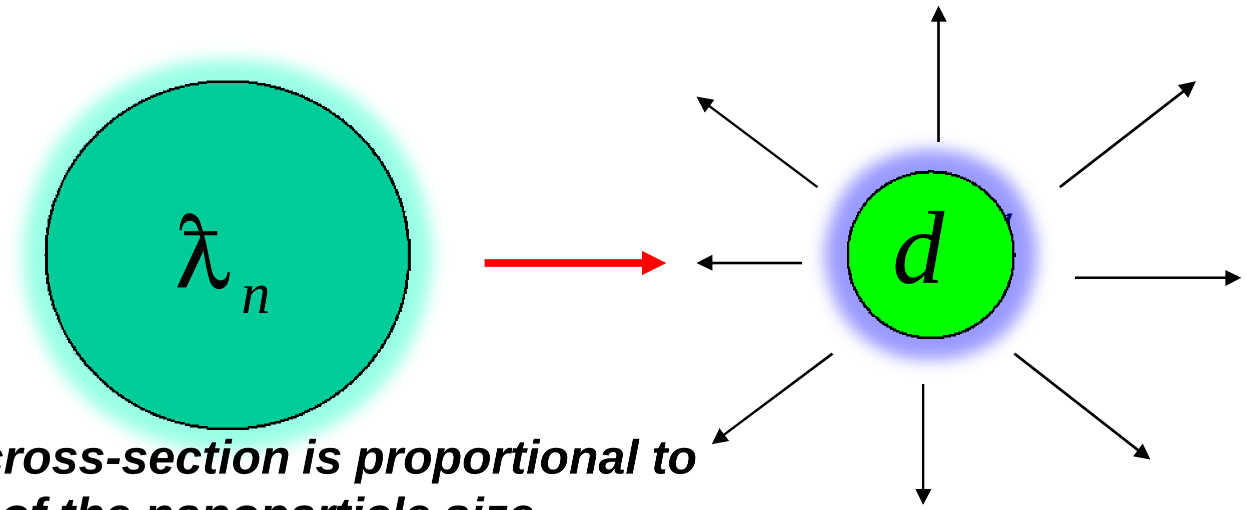
Crystals readjusted



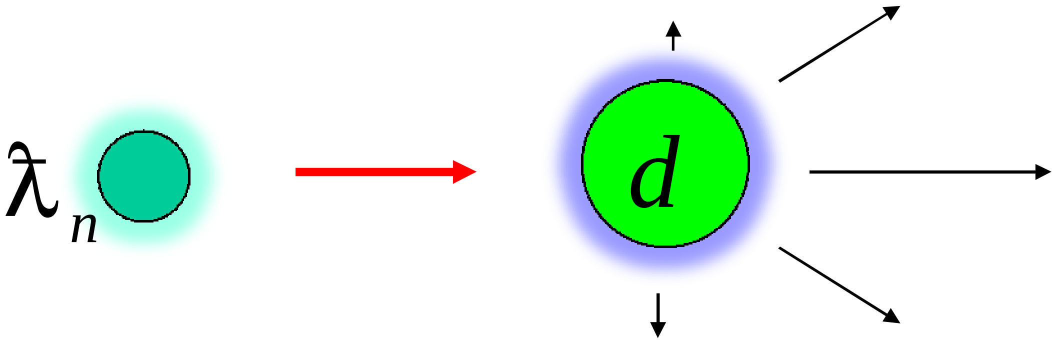
7.2×10^8 n $cm^{-2}s^{-1}$

Possible upgrade is based on Neutron scattering on nanoparticles

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

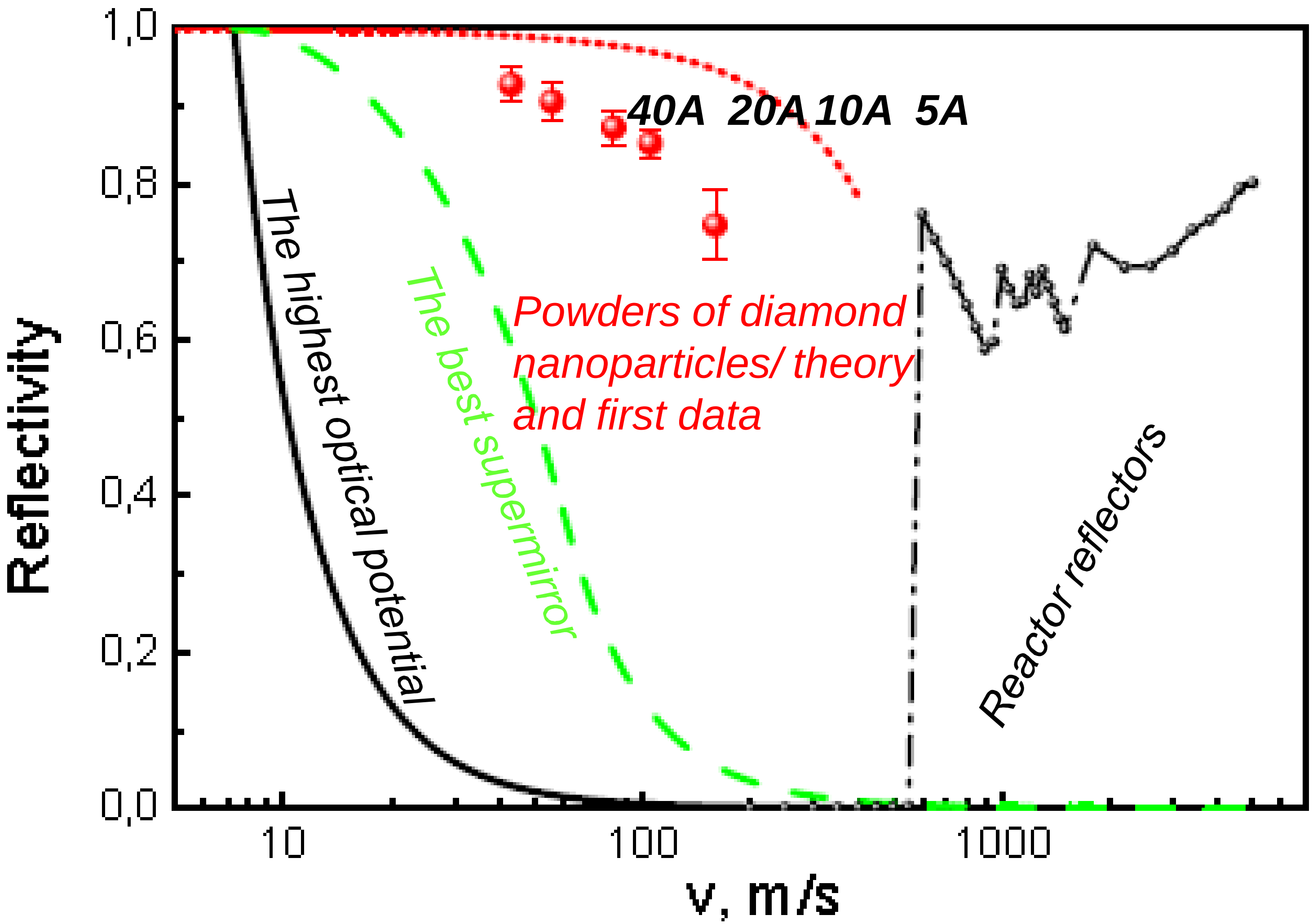


the scattering cross-section is proportional to 6-th power of the nanoparticle size

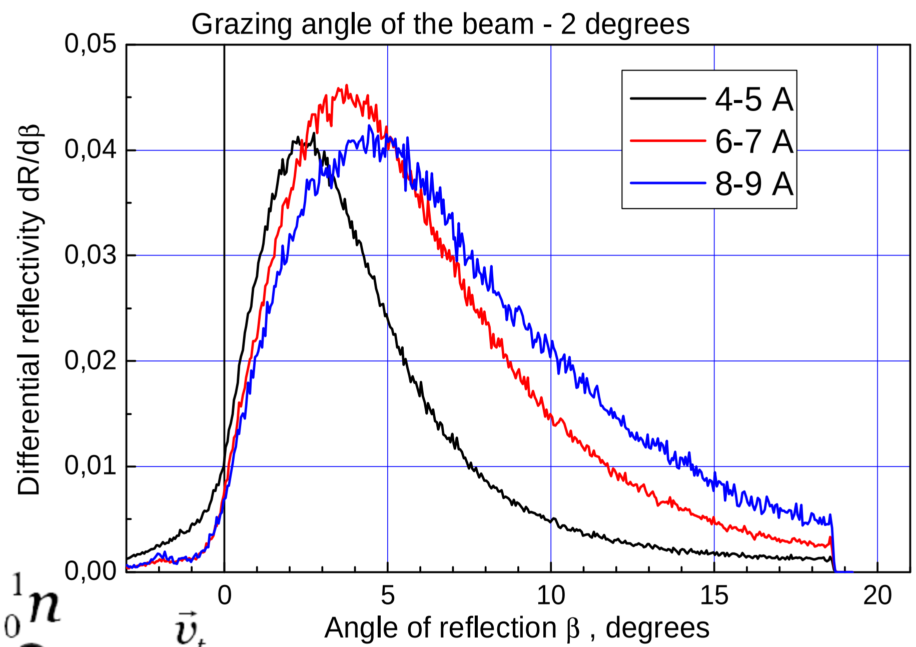


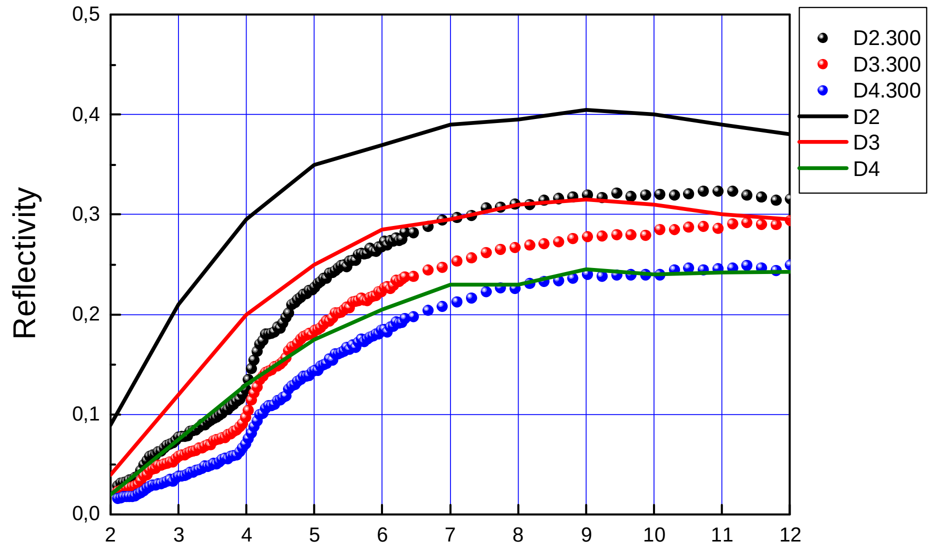
Storage of very cold neutrons (VCN) in traps

Storage of very cold neutrons (VCN) in traps

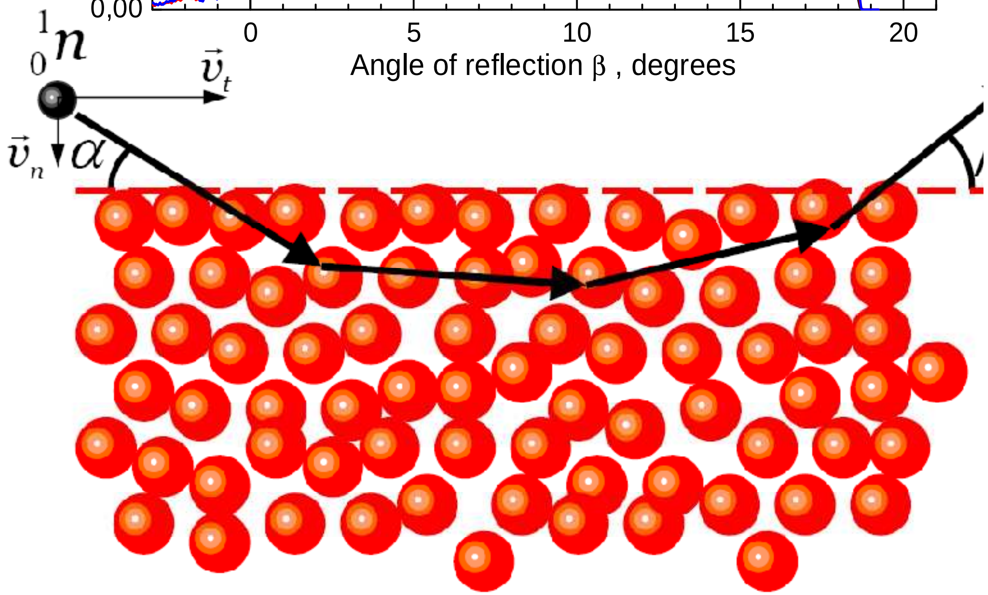


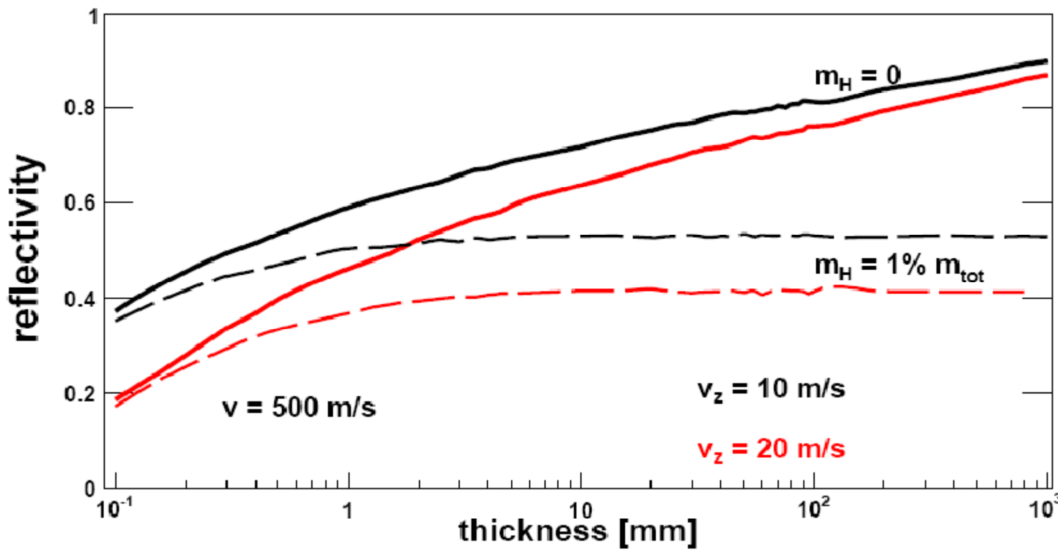
Quasi-specular reflection of cold neutrons from powders



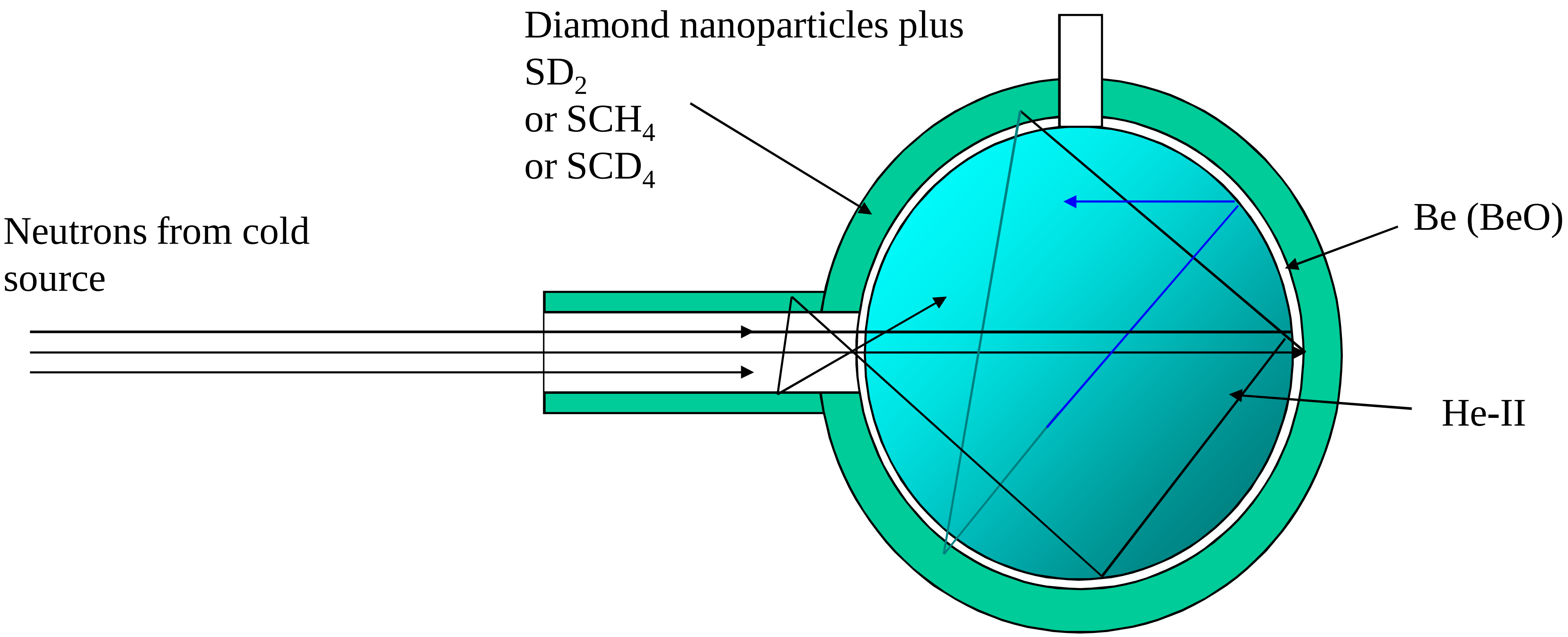


GRAZING NEUTRON AT ULTRADIAMOND90

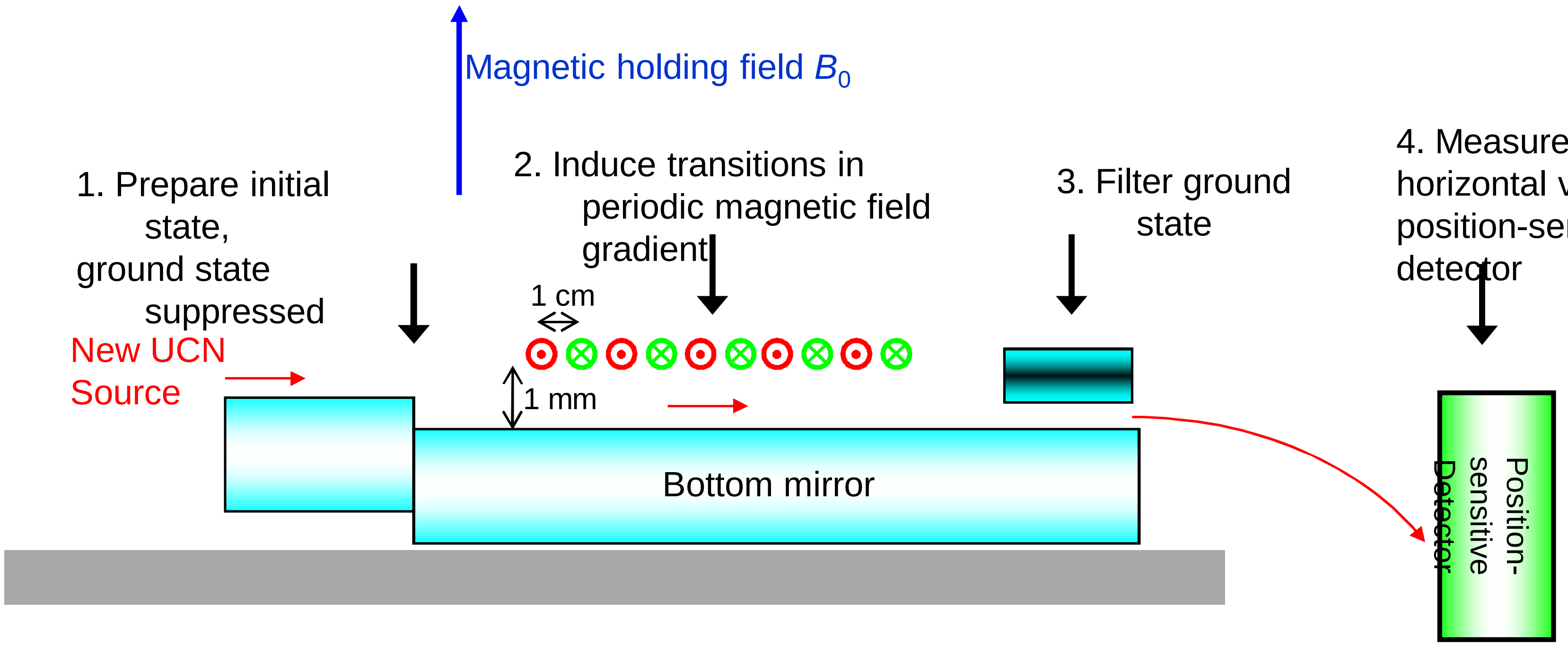


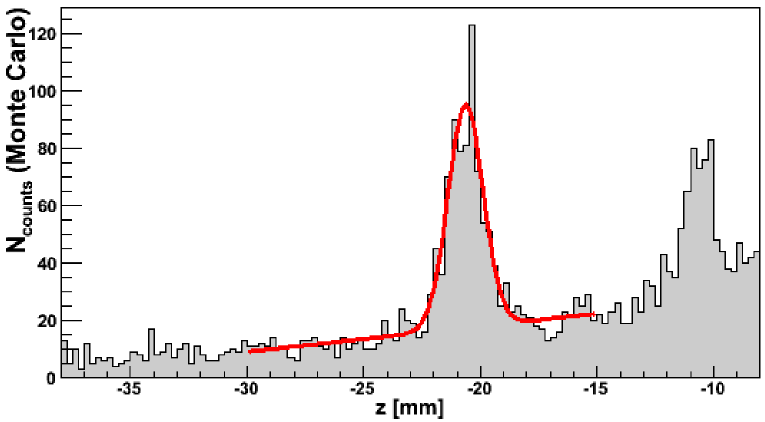


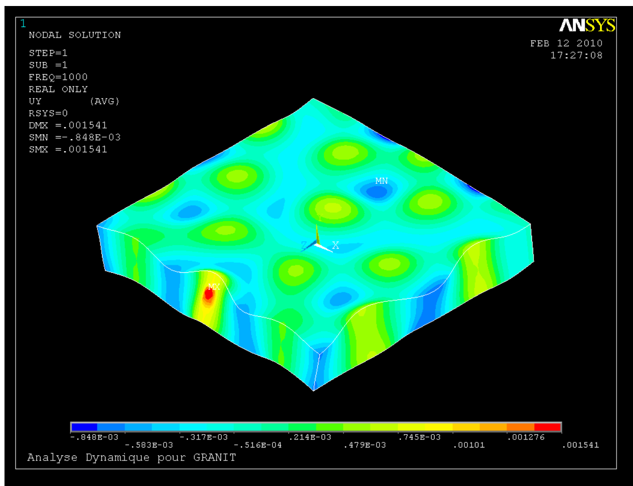
A concept of Virtual neutron source for UCN production

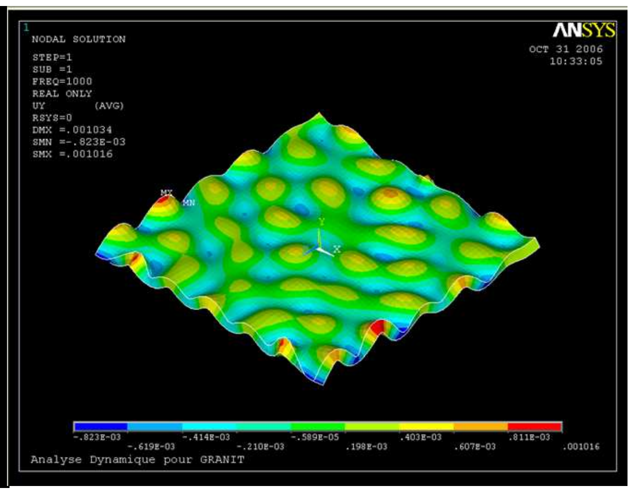


GRANIT
on methods of excitation the transitions







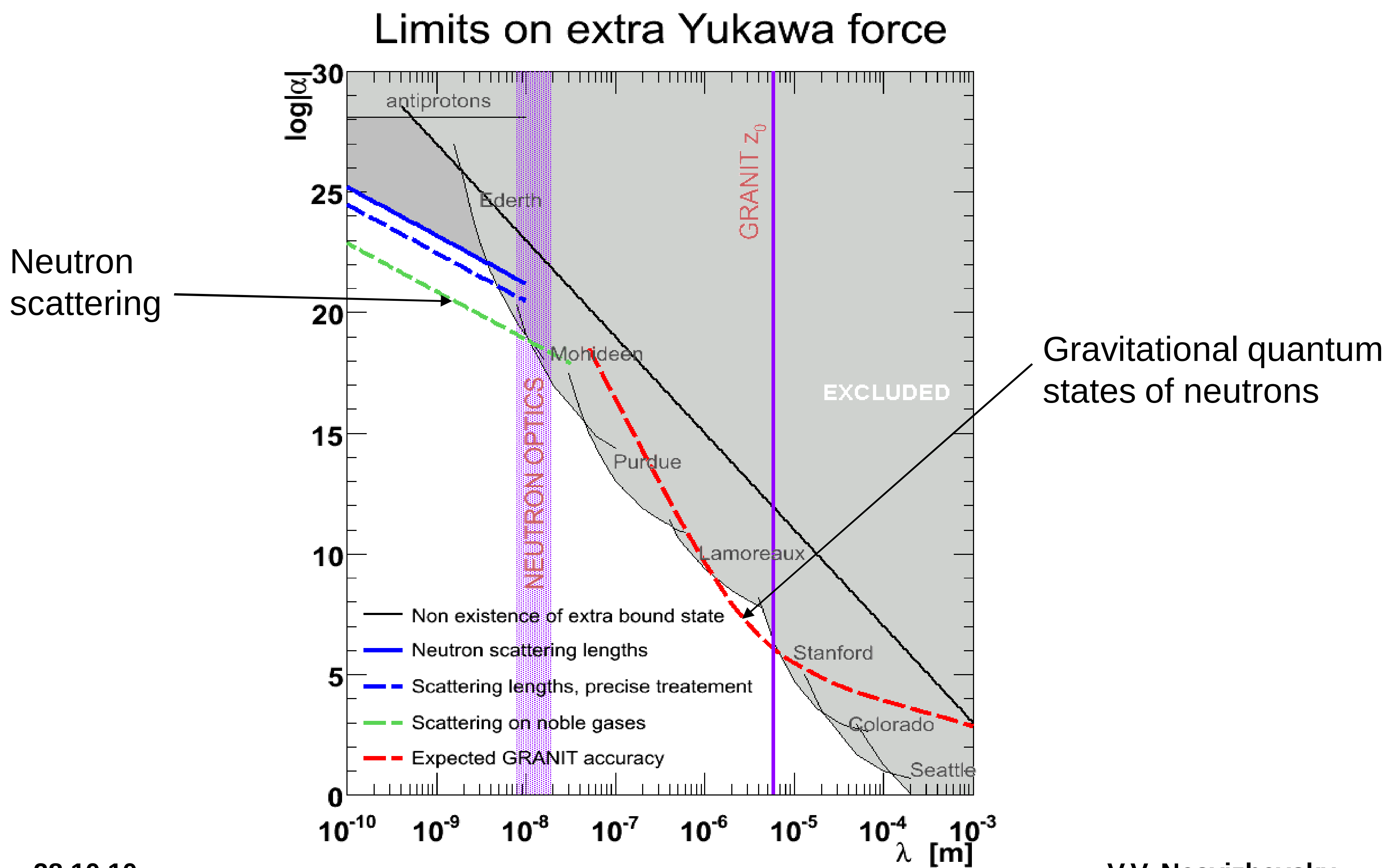


Applications

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;***
-***Constraints for physics beyong the Standard model;***
-***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....***

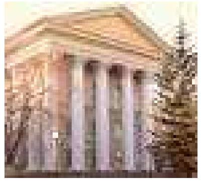
Constrains for short-range forces

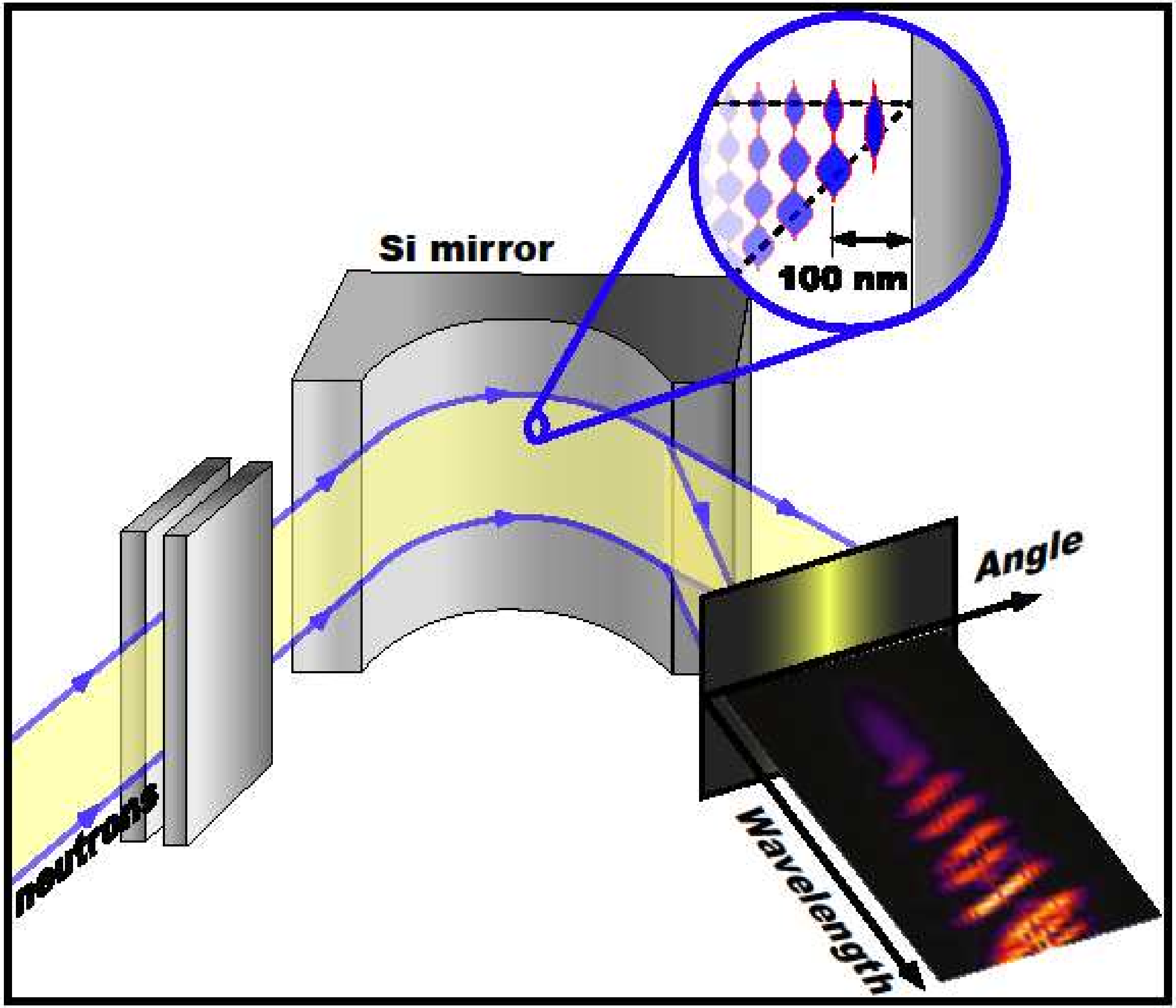


Conclusion (on gravitational quantum states)

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. This phenomenon could be used 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





Neutron whispering gallery

nature physics LETTERS
PUBLISHED ONLINE: 13 DECEMBER 2009 | DOI: 10.1038/NPHYS1478

***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

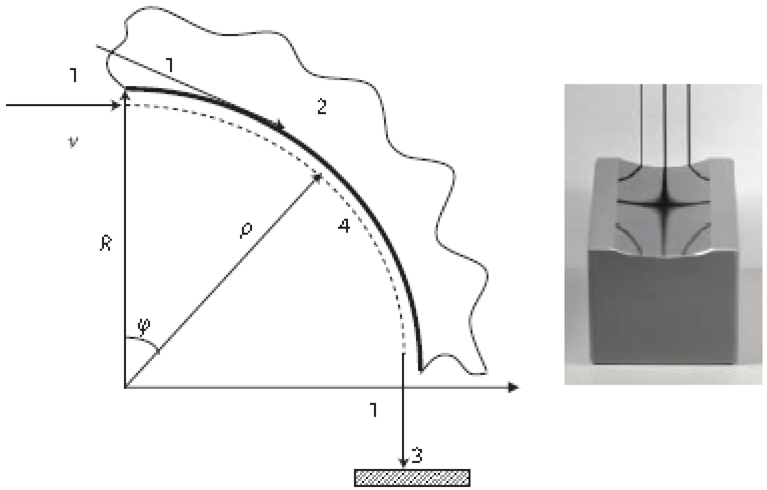
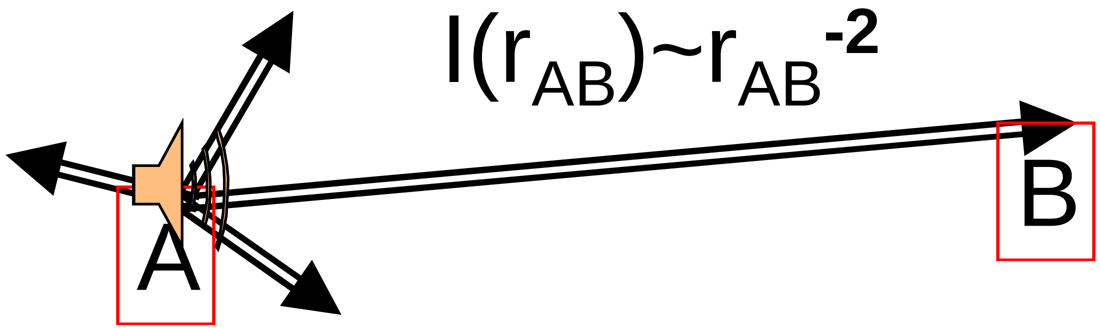


Figure 1 | A scheme of the neutron centrifugal experiment. 1: Classical trajectories of incoming and outgoing neutrons, 2: cylindrical mirror, 3: neutron detector, 4: quantum motion along the mirror surface. Inset: A photo of the single-crystal cylindrical silicon mirror used for the presented experiments,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

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



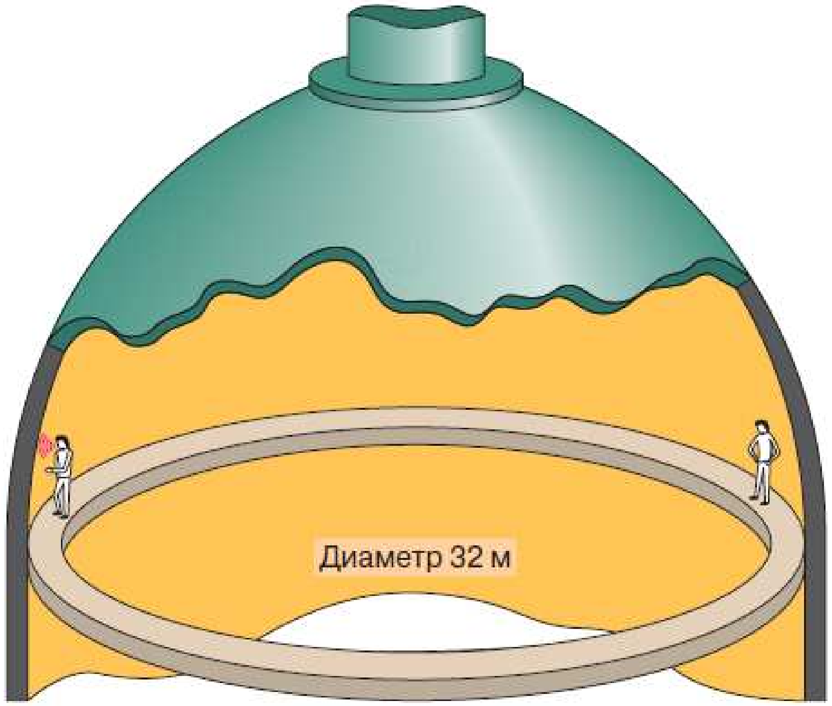
Any wave

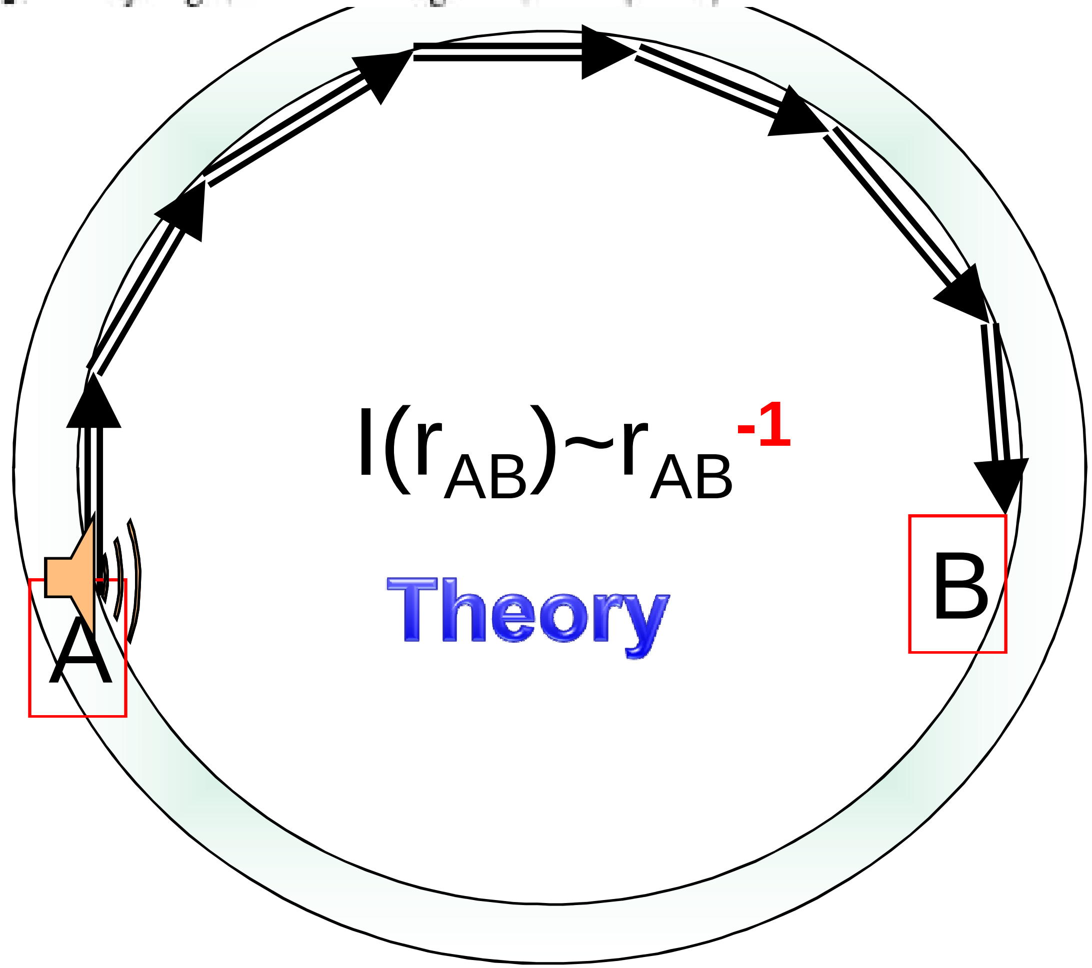
Neutron whispering gallery

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

NEUTRONS FOR SCIENCE

[1] J. W. Strutt Baron Rayleigh, *The Theory of Sound* (Macmillan, London 1878), Vol. 2.
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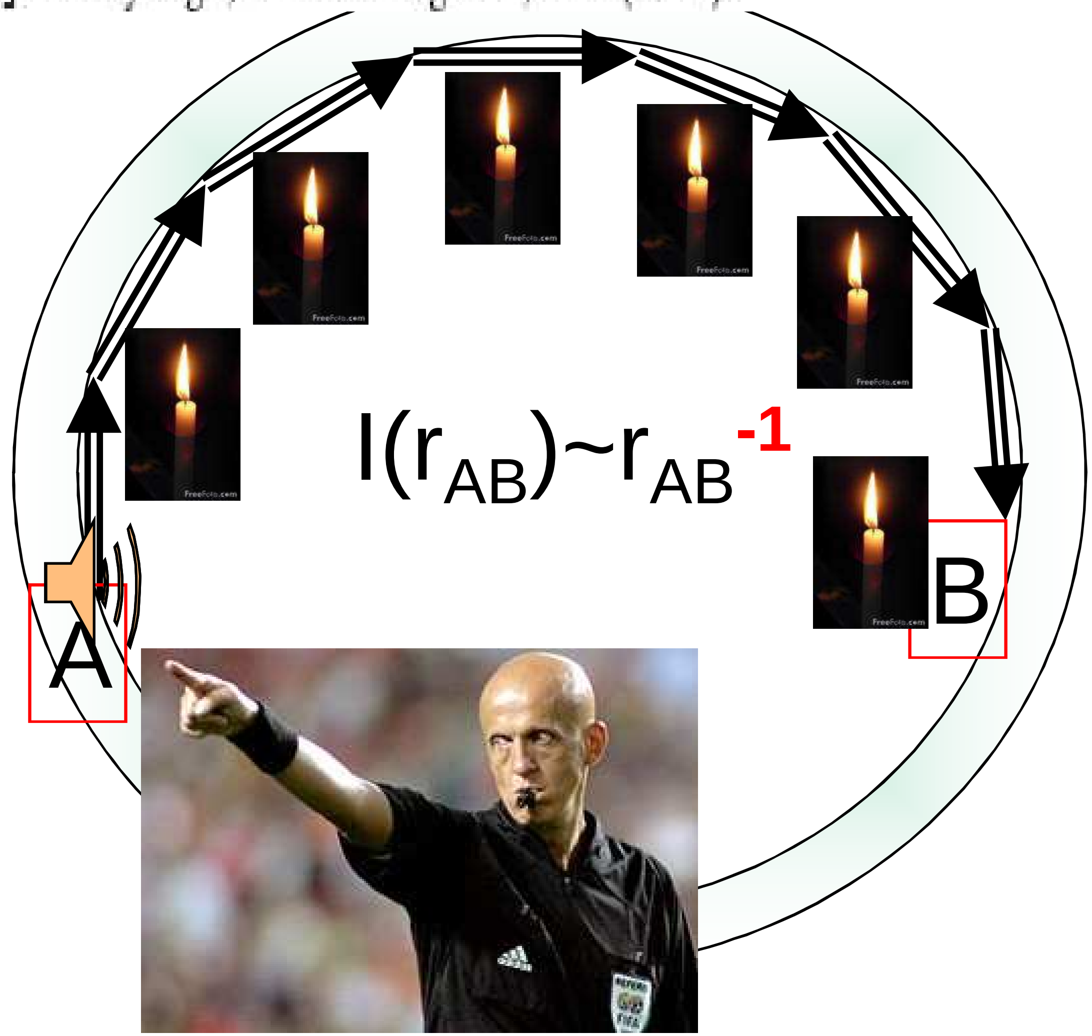

Experiment

Neutron whispering gallery

[1] J. W. Strutt Baron Rayleigh, *The Theory of Sound* (Macmillan, London 1878), Vol. 2.
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Experiment

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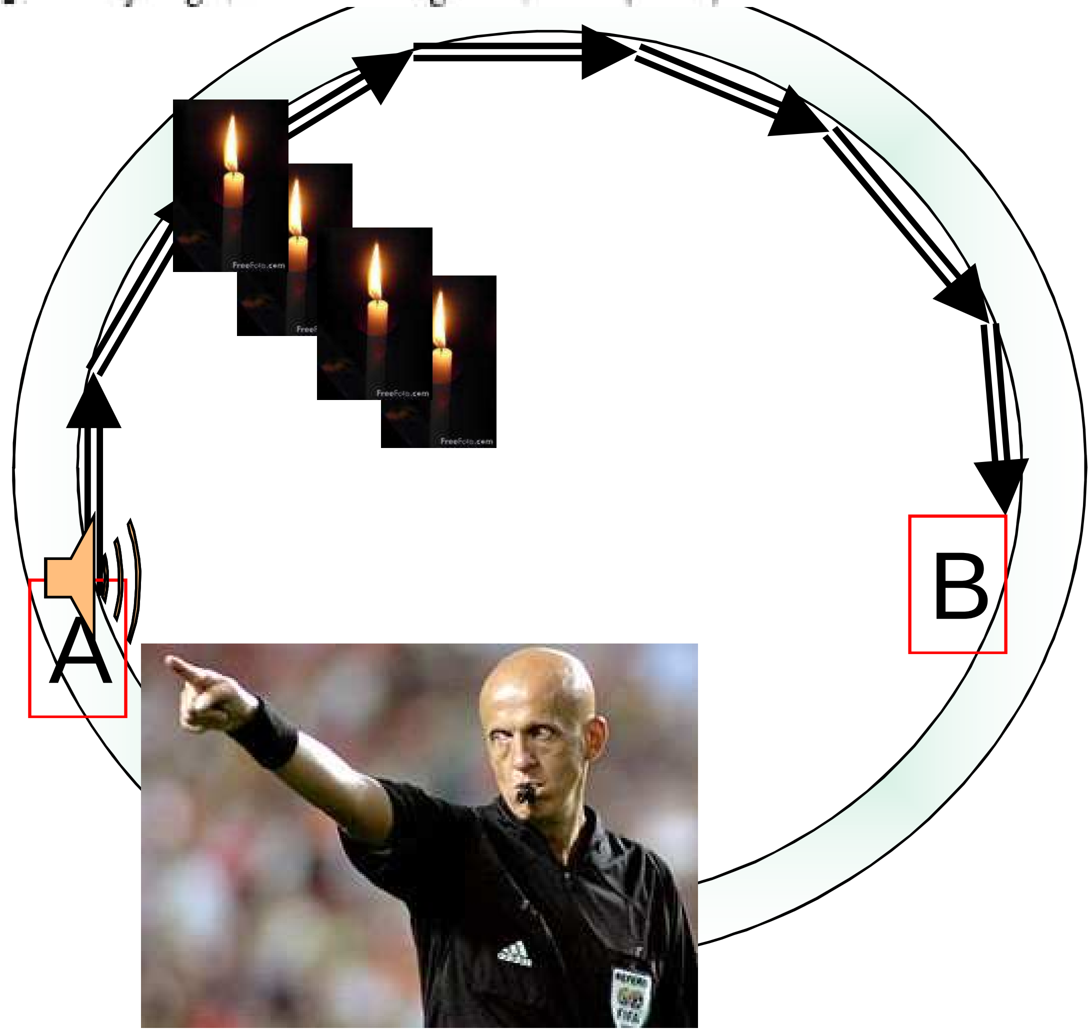


and many other examples

Neutron whispering gallery / proposal

PHYSICAL REVIEW A 78, 1 (2008)

Centrifugal quantum states of neutrons

V. V. Nesvizhevsky* and A. K. Petukhov
Institut Laue-Langevin (ILL), 6 rue Jules Horowitz, F-38042, Grenoble, France

K. V. Protasov
Laboratoire de Physique Subatomique et de Cosmologie (LPSC), IN2P3-CNRS, UJFG, 53, Avenue des Martyrs, F-38026, Grenoble, France

A. Yu. Voronin
P.N. Lebedev Physical Institute, 53 Leninsky prospekt, 119991, Moscow, Russia

(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.

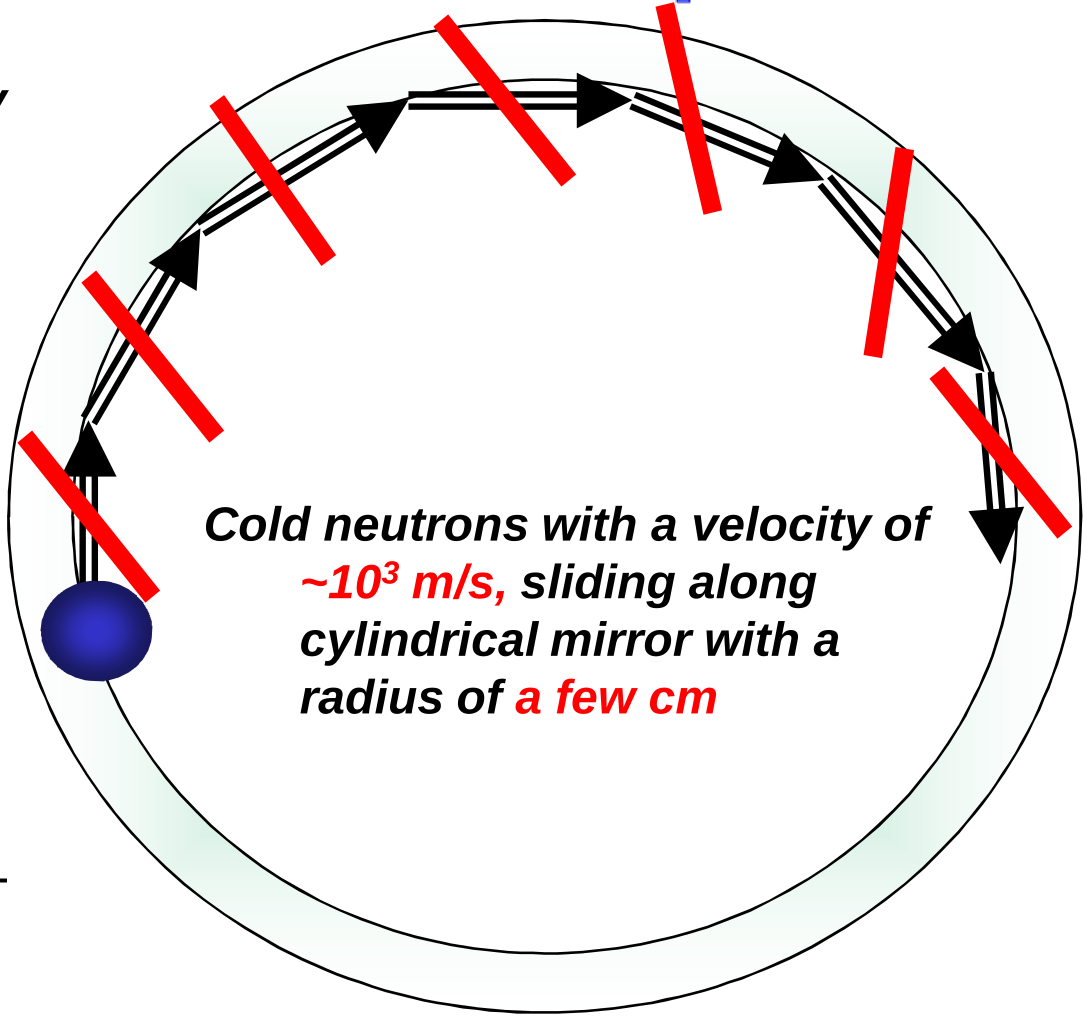
Neutron whispering gallery

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:

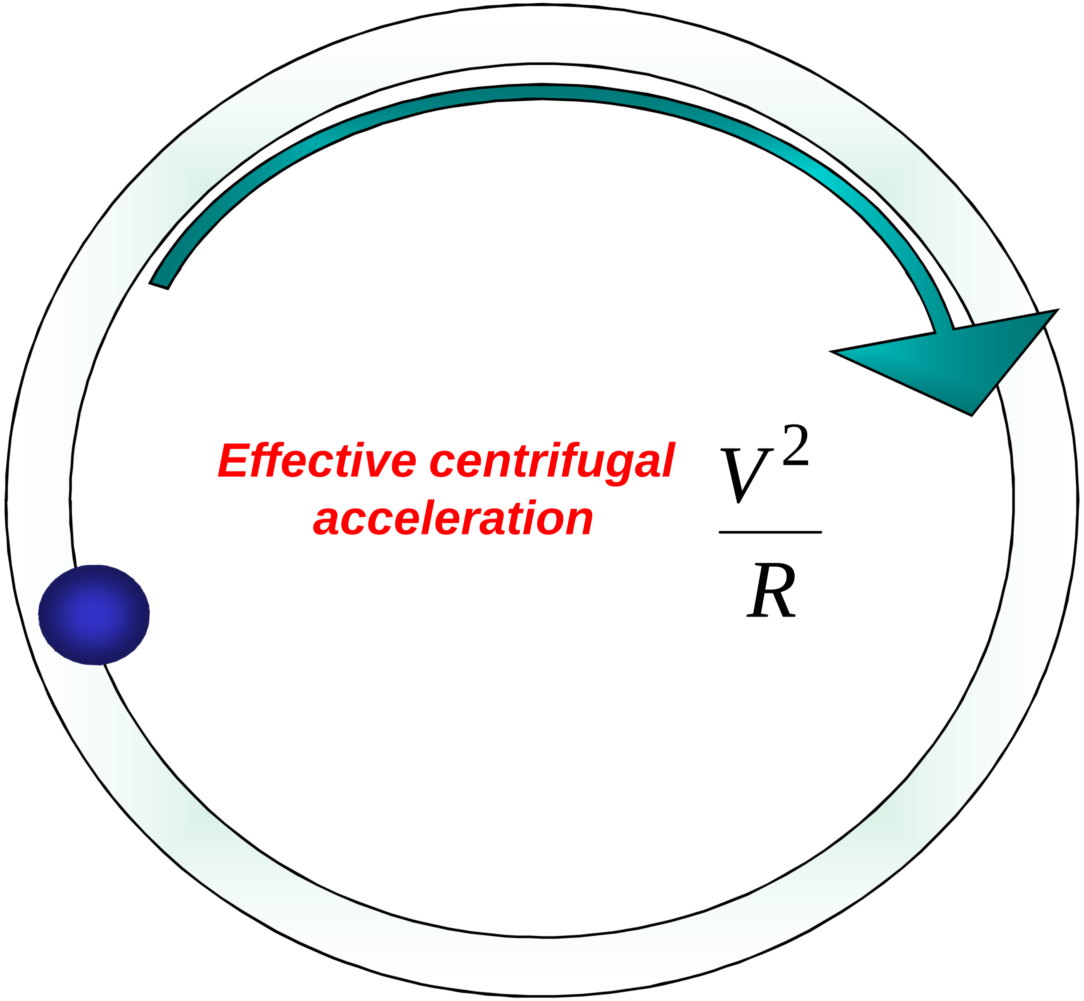
- Mabuchi H. & Kimble H.J. Atom galleries for whispering atoms – binding atoms in stable orbits around an optical resonator. *Opt. Lett*. **19**, 749-751 (1994).
- Vernooy D. M. & Kimble H.J. Quantum structure and dynamics for atom galleries. *Phys. Rev. A* **55**, 1239-1261 (1997).

Characteristic parameters



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



$$\frac{V^2}{R}$$

Neutron whispering gallery

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

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

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

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

Precise solution

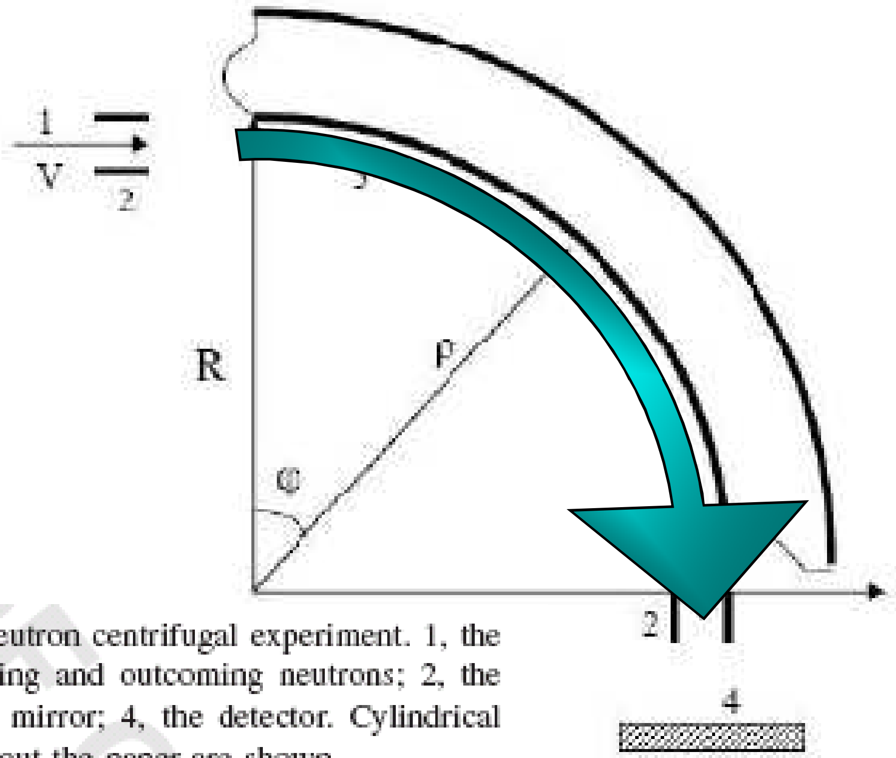
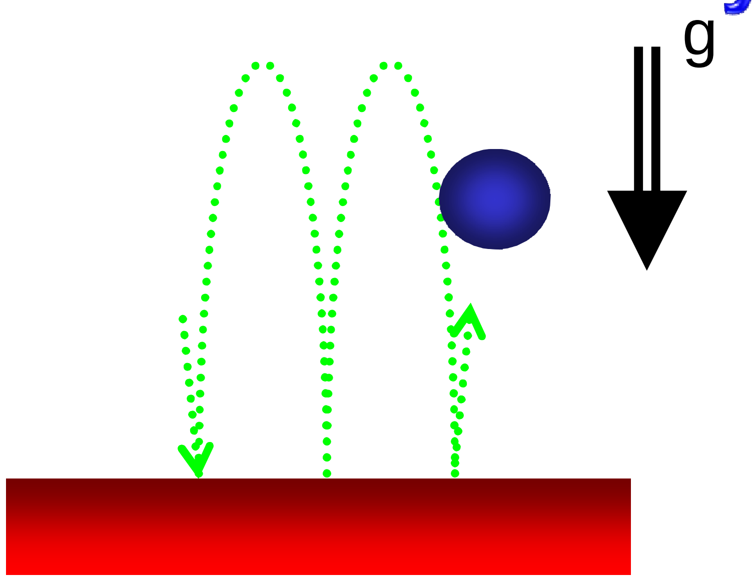


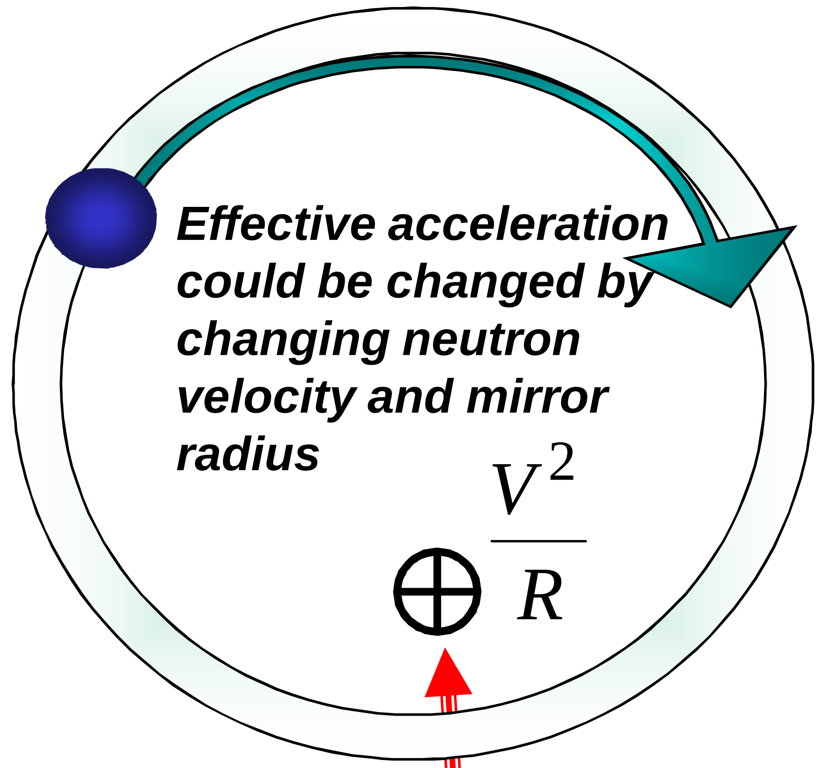
FIG. 1. A scheme of the neutron centrifugal experiment. 1, the classical trajectories of incoming and outcoming neutrons; 2, the collimators; 3, the cylindrical mirror; 4, the detector. Cylindrical coordinates $\rho-\varphi$ used throughout the paper are shown.

Comparison to gravitational quantum states of neutrons

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

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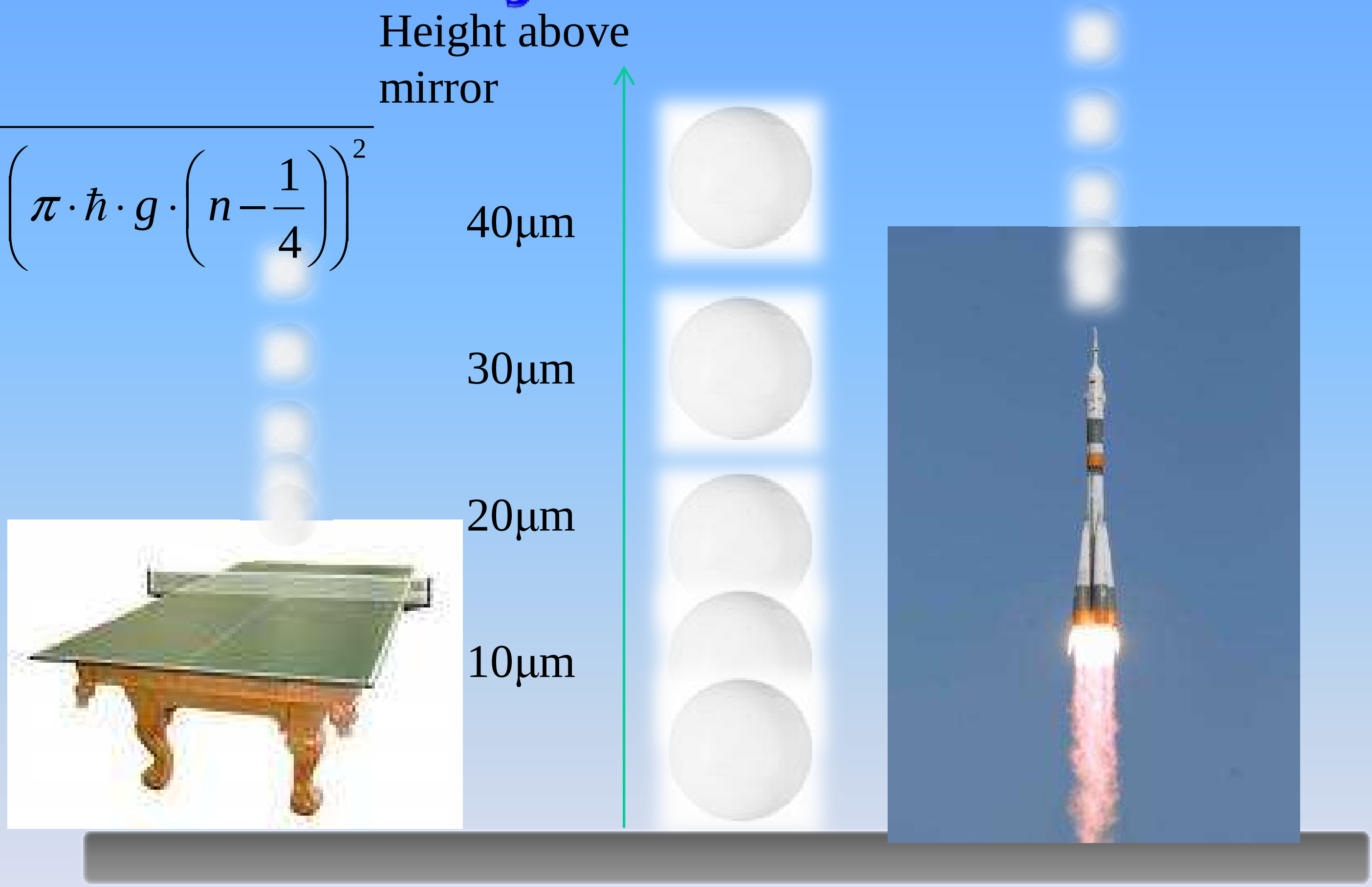


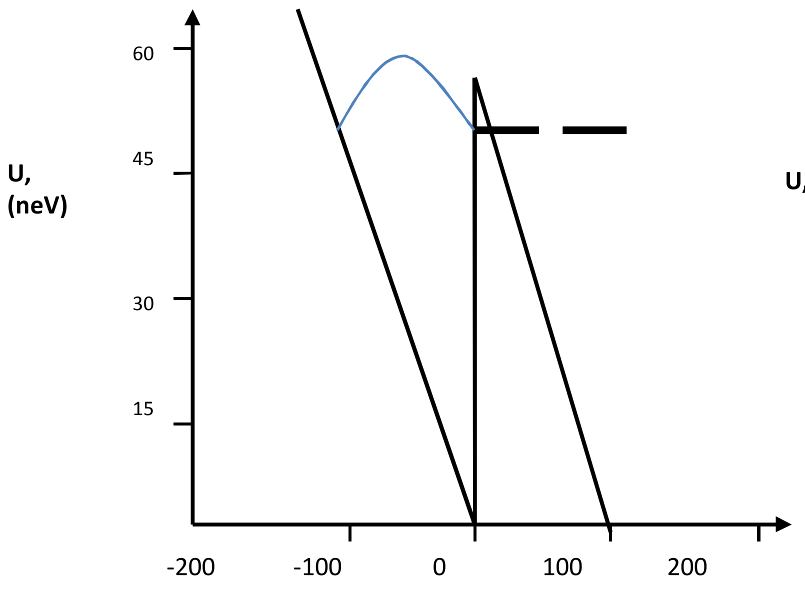
Illustration for quantum motion of an object above mirror in gravitational field and that in accelerating frame. Positions of the ball correspond to its most probable heights in 5th quantum state. The vertical scale corresponds to the neutron mass.

Methods of observation

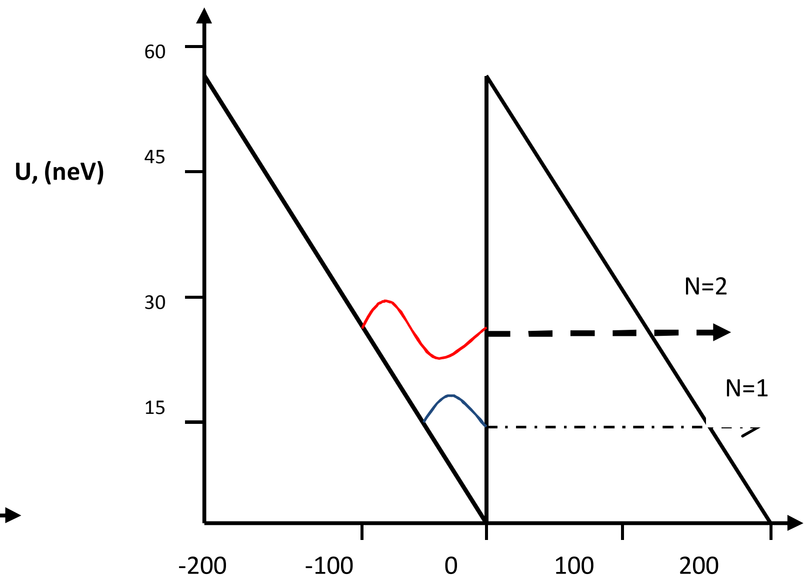
$$\Gamma_n = \left(\frac{\hbar^2 M v^4}{2R^2}\right)^{1/3} \frac{\sqrt{z_0 - \lambda_n}}{z_0} \exp\left[-\tfrac{4}{3}\left(z_0 - \lambda_n\right)^{3/2}\right]$$

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

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



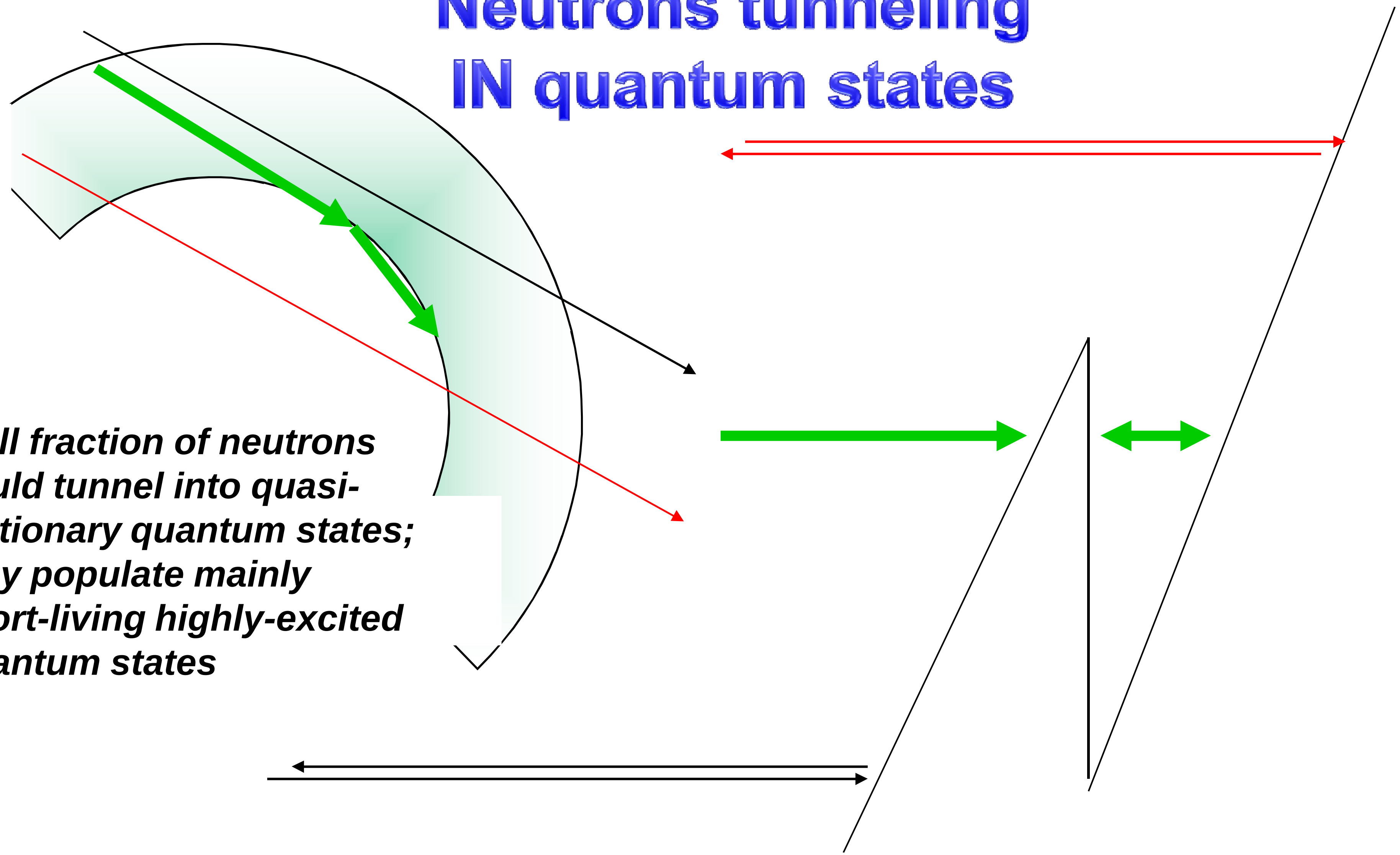
λc



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

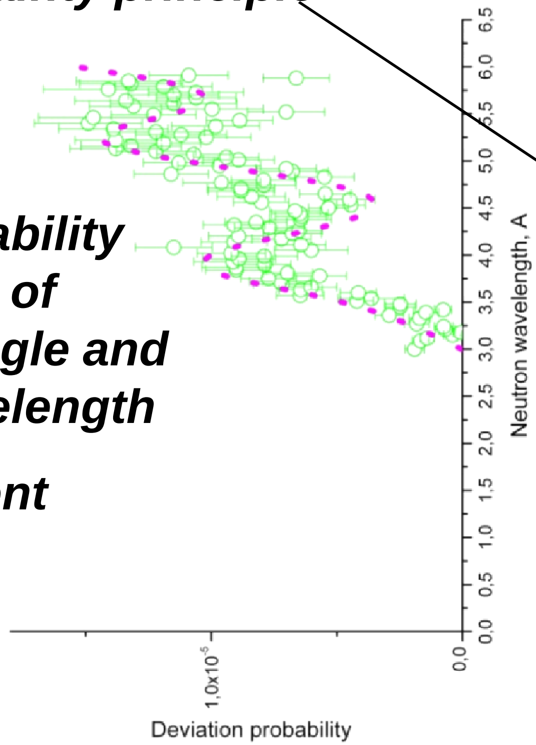
Neutrons tunneling IN quantum states

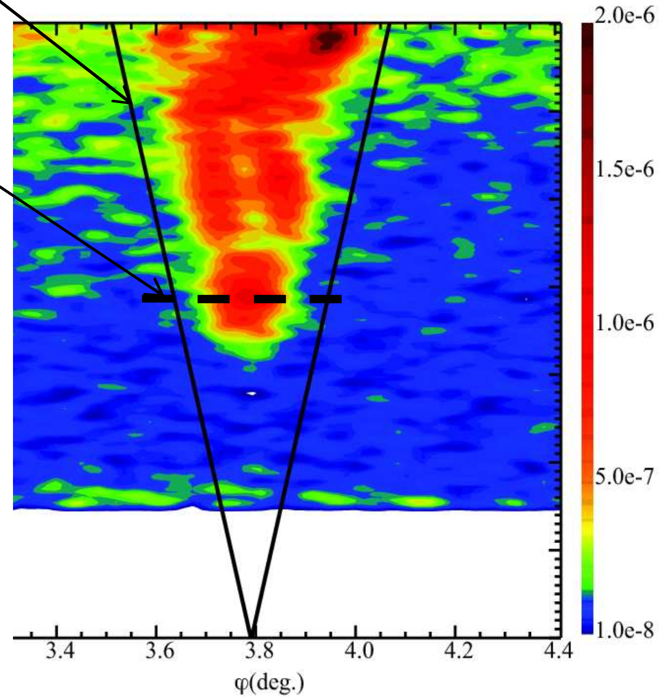
Solid lines define « classical » shape of the signal; horizontal line indicates estimation of the neutron wavelength resulting from the uncertainty principle

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

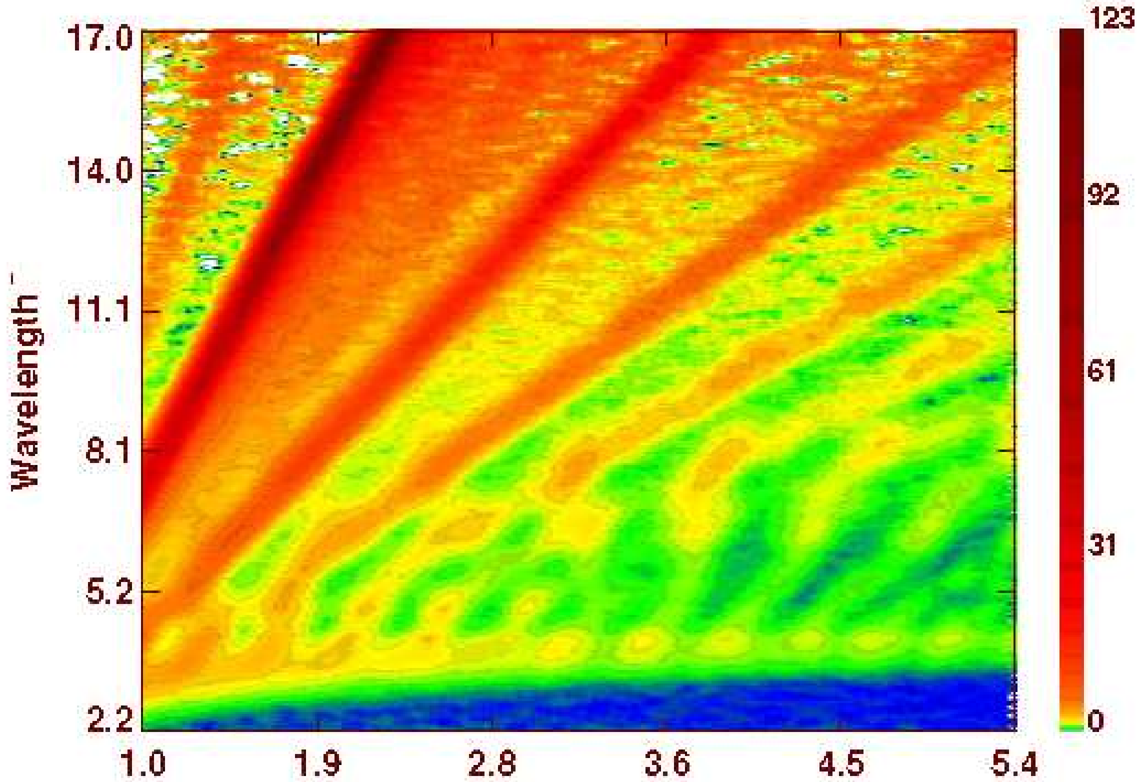
theory/experiment



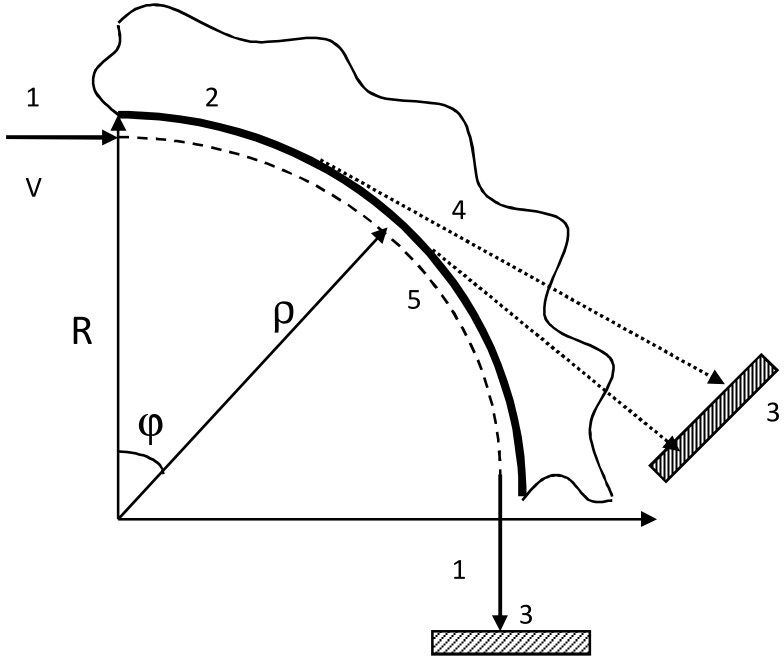


Neutrons tunneling OUT of quantum states

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



Methods of observation



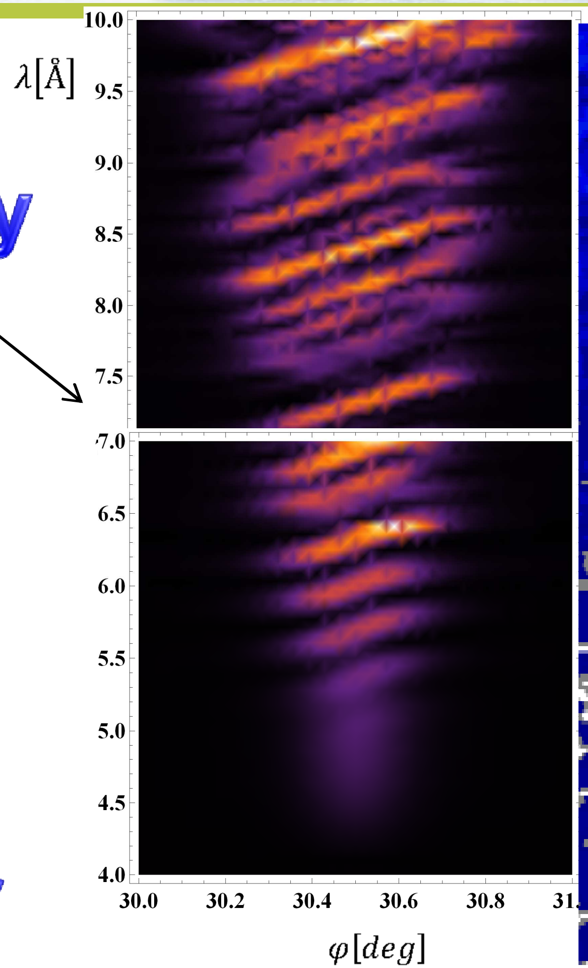
Neutrons entering from edge of truncated cylindrical mirror

D17 instrument at the ILL

1) ***Tangential neutron velocity is defined by time-of-flight method;***
2) ***Scattering angle (radial velocity) is measured in a position-sensitive neutron detector.***

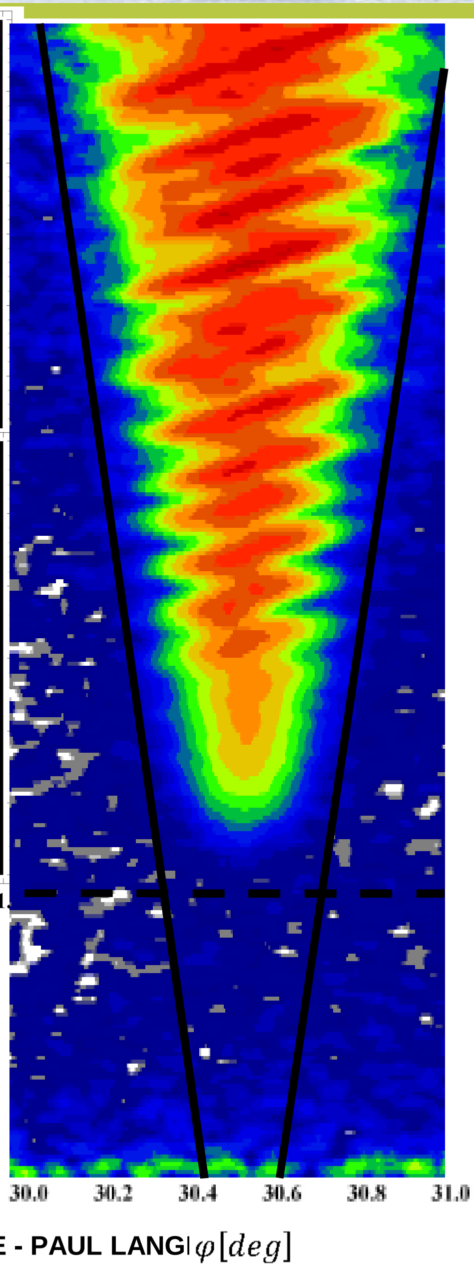
Results

Theory

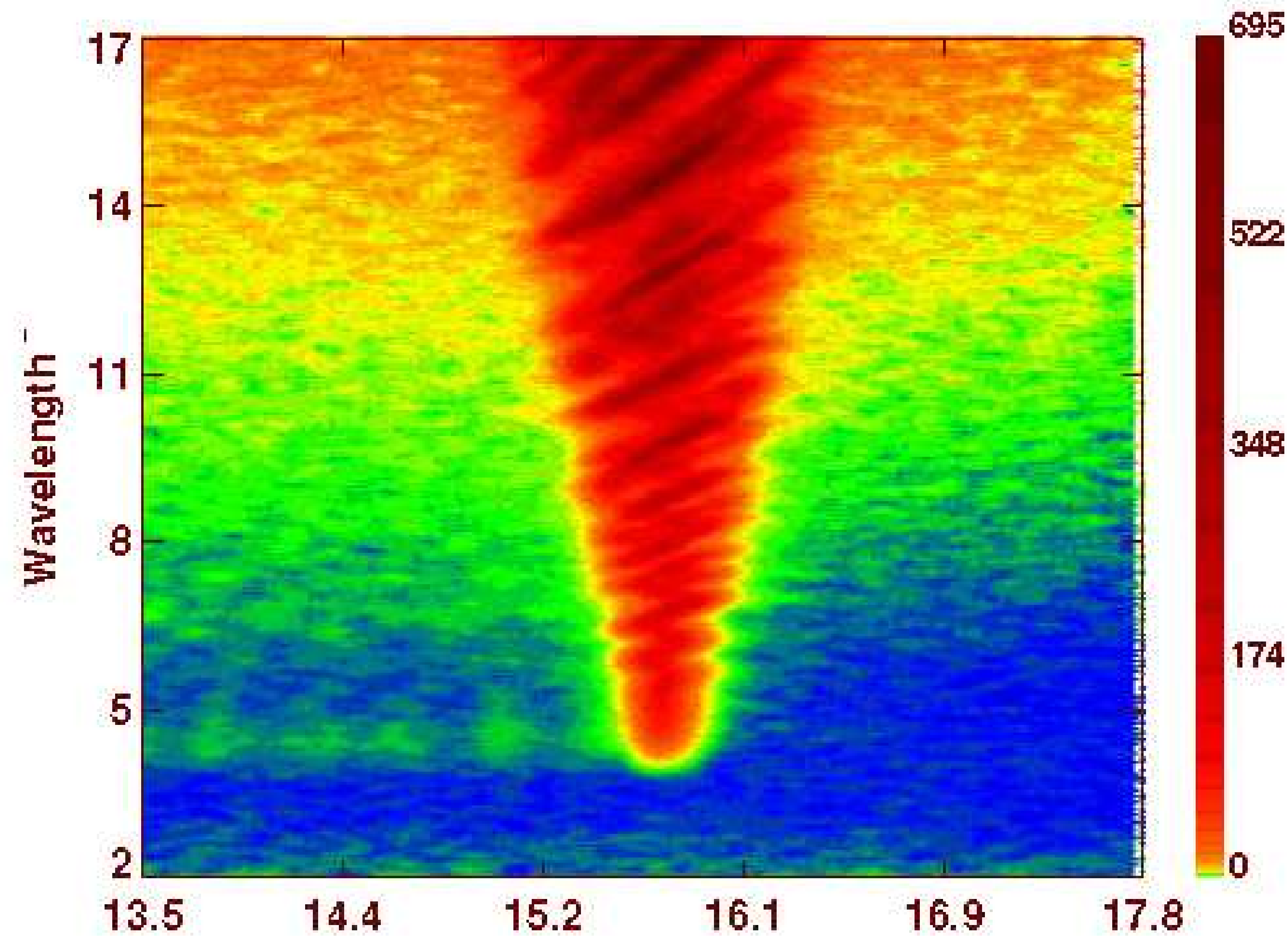


Neutrons entering from mirror edge

Experiment

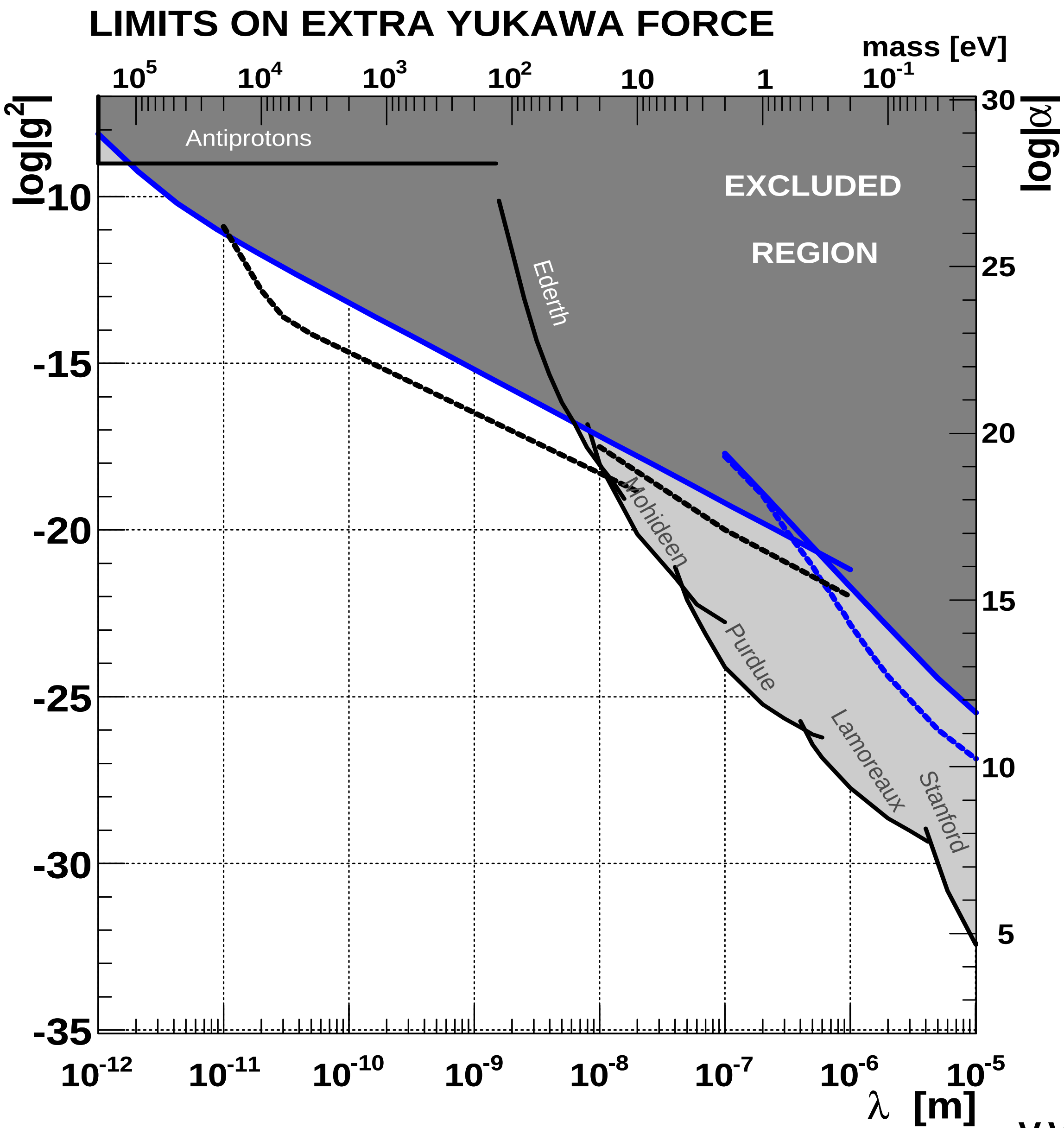


Results



17
14
11
8
5
2
Wavelength
13.5
14.4
15.2
16.1
16.9
17.8
695
522
348
174
0
$\varphi[deg]$

Sensitivity to additional forces

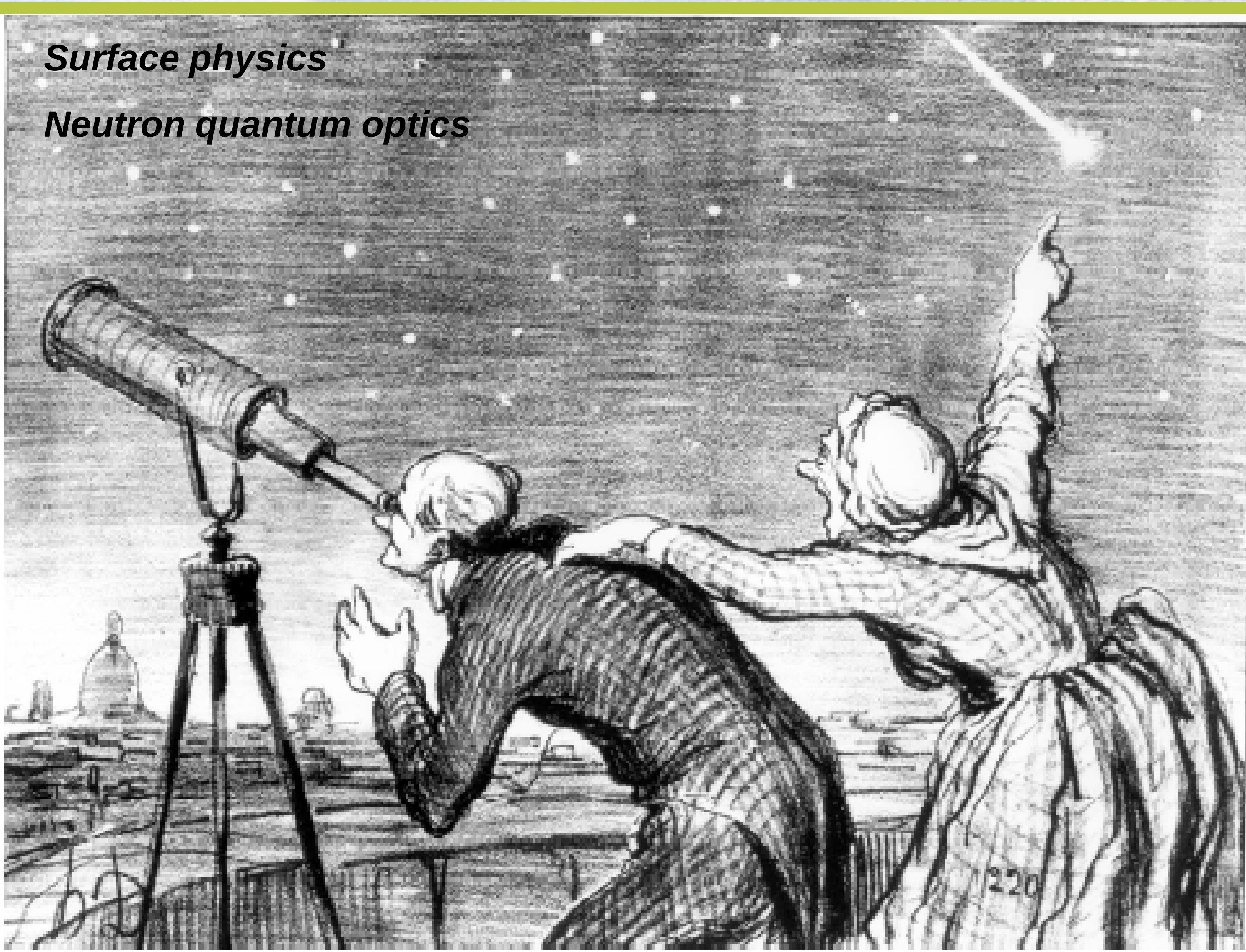


V.V. Nesvizhevsky

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