Gravitational and centrifugal quantum states of matter (neutrons) and anti-matter (anti-hydrogen atoms)

1. Gravitational and centrifugal quantum states of matter and anti-matter could be considered as the first direct verification of the weak equivalence principle for matter and anti-matter objects in quantum states
2. Comparison of perspective experiments with anti-matter atoms to recent observations of gravitational and centrifugal quantum states of slow neutrons
3. Long lifetimes of neutrons and anti-hydrogen atoms? in such quantum states allow one using them for various precision studies

Comparison of gravitational and centrifugal quantum states

Gravity / Acceleration

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

For more information, see V.V.N. Physics-Uspekhi 53 (2010) 645

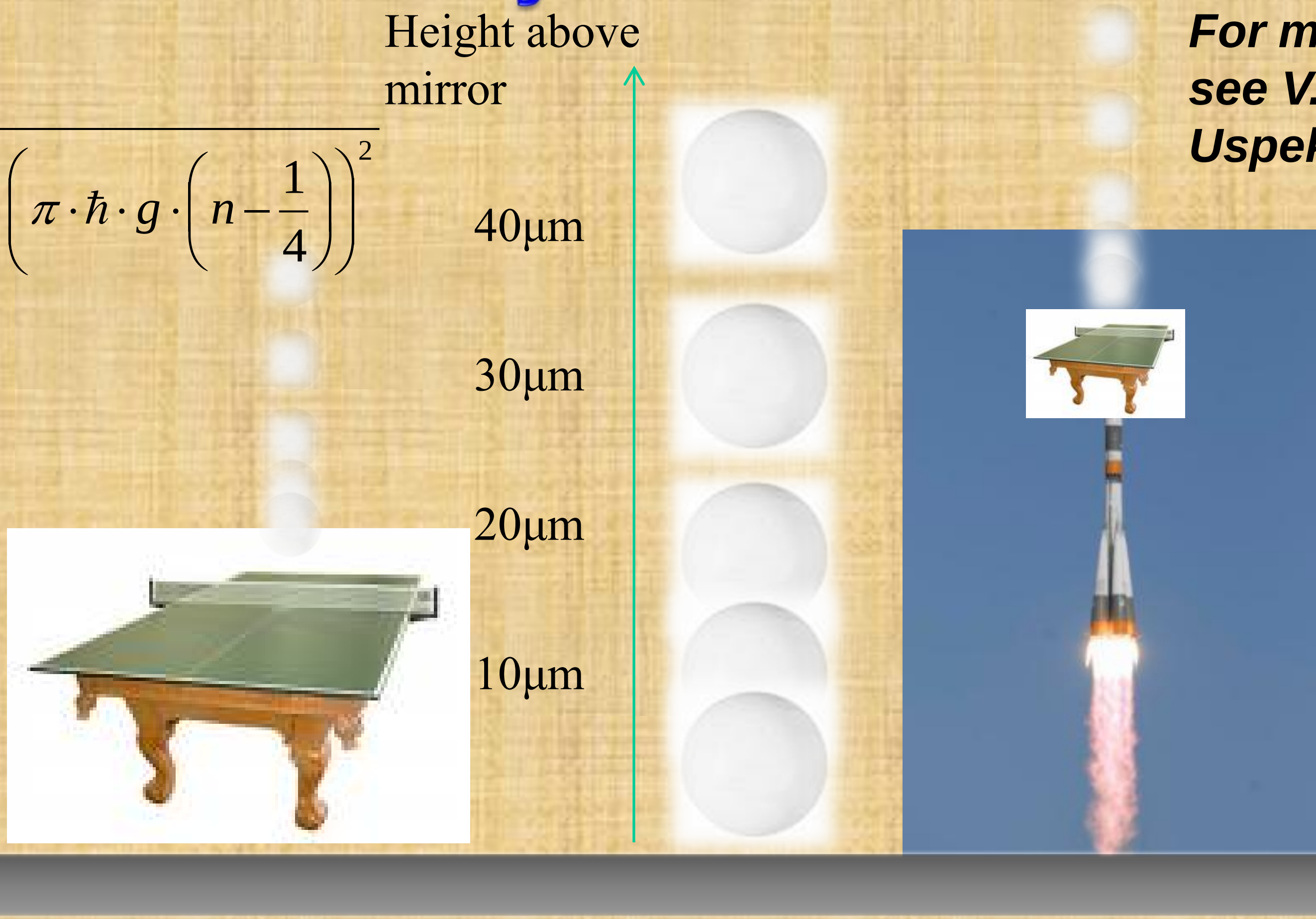
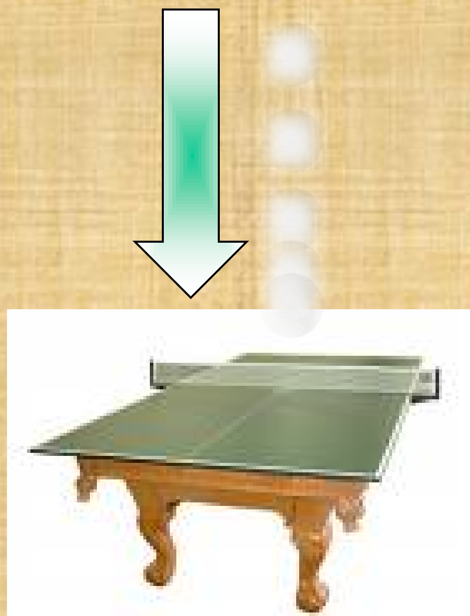


Illustration for quantum motion of an object above a mirror in the gravitational field and that in the accelerating frame. Positions of the ball correspond to the most probable heights of a neutron (or an anti-hydrogen atom) in the 5th quantum state.

Matter / Anti-matter



Gravitational properties of matter have never been measured directly!

but aimed at, in particular, in GBAR project

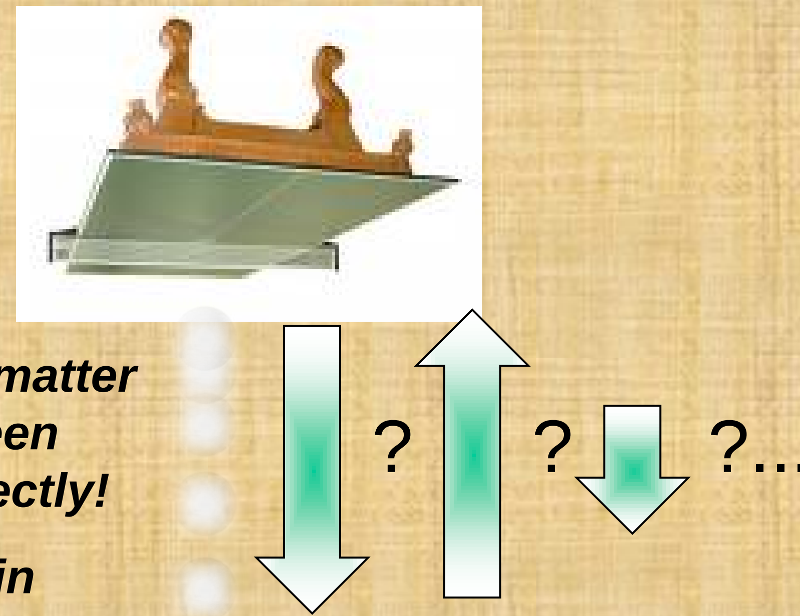


Illustration for quantum motion of a matter object and an anti-matter object above a mirror in a gravitational field.

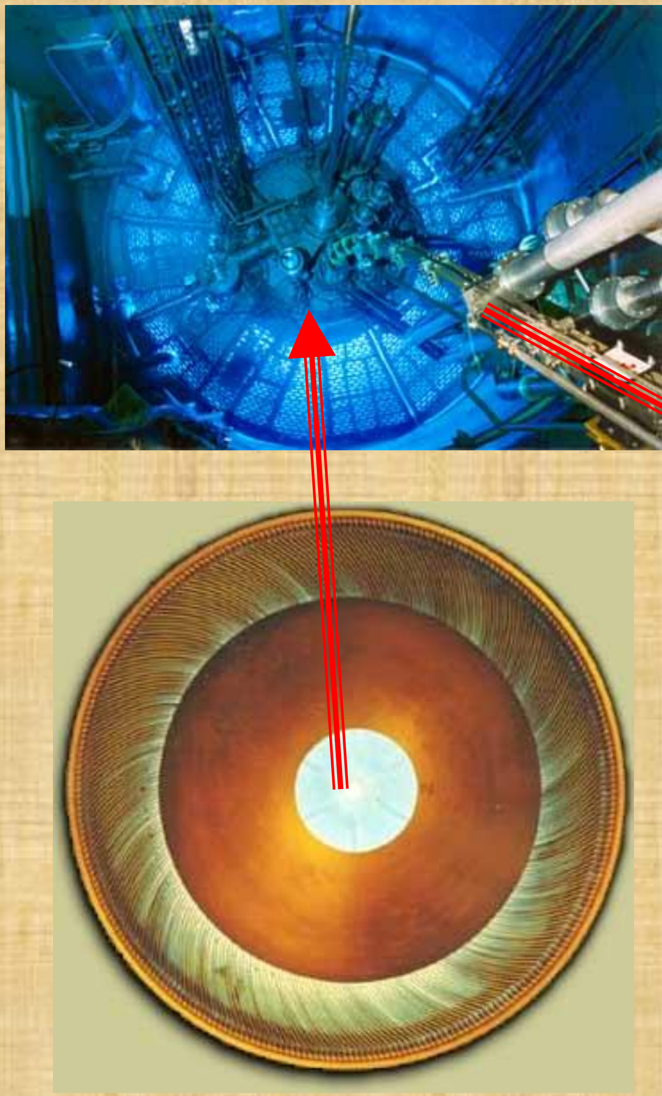
GRANIT-2010 Workshop
14-19 February 2010, Les Houches, France

Granit
Gravitational Neutron Induced Transitions

Countries ~12
Europe, Asia, USA, Australia
For more information, see Compt. Rend. Phys. 12 (2011) 703

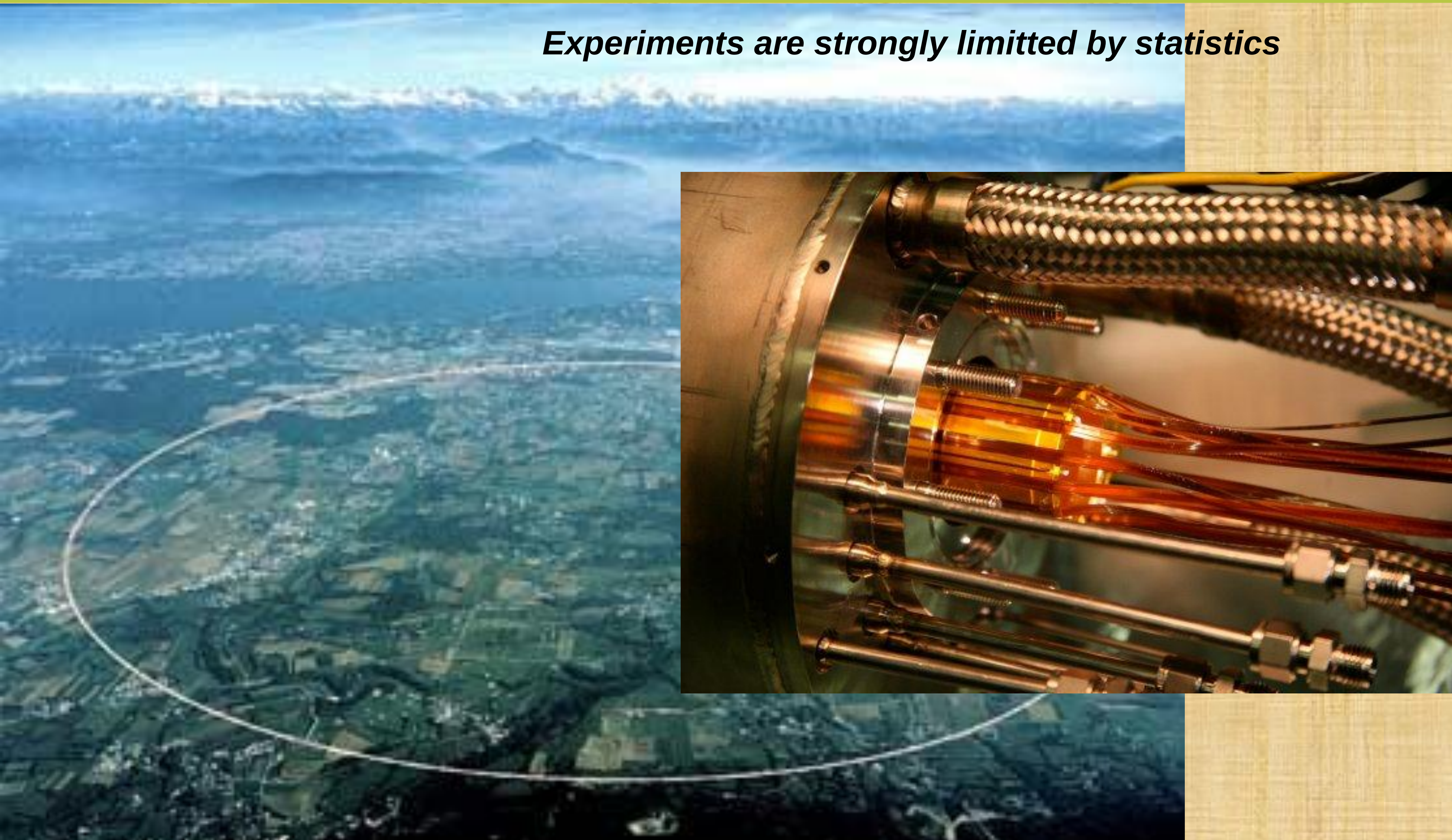
Neutron: ILL, Grenoble: The largest worldwide research reactor

Experiments are strongly limitted by statistics



Anti-hydrogen: CERN, Geneve. The largest worldwide particle accelerator facility

Experiments are strongly limitted by statistics



Gravitational quantum states of ultracold neutrons (UCN)

NEUTRONS FOR SCIENCE

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, Germa*
‡ *Petersburg Nuclear Physics Institute, Orlova Roscha, Gatchina, Leningrad R-188350, Russia*
§ *Joint Institute for Nuclear Research, Dubna, Moscow reg. R-141980, Russi*

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

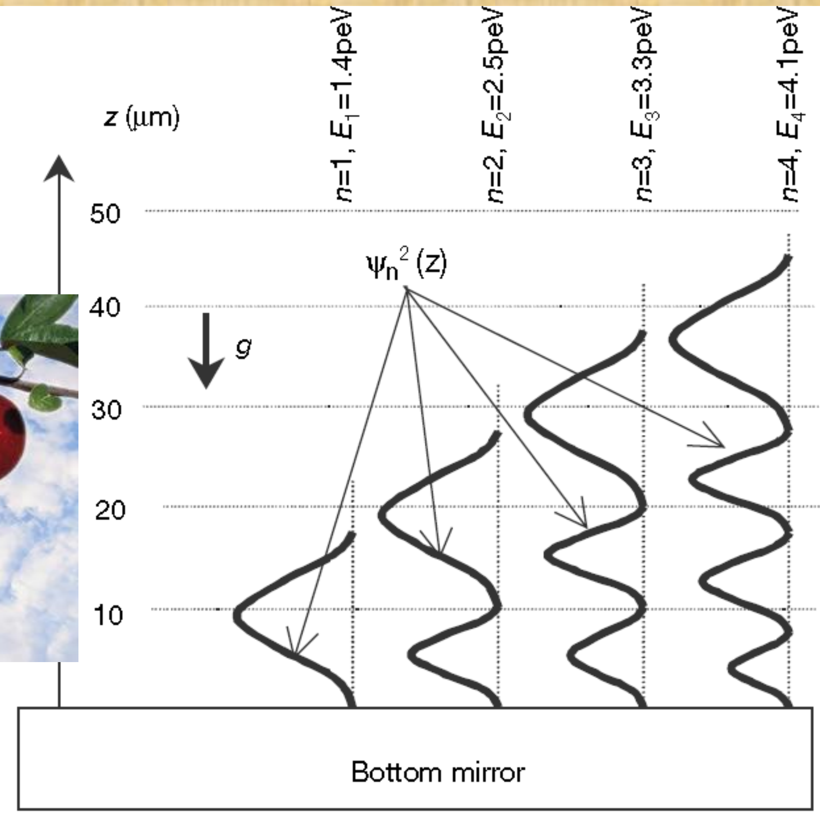
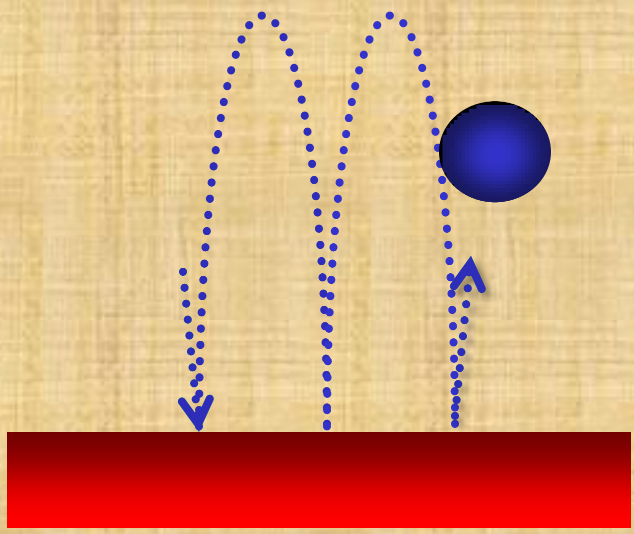


Figure 1 Wavefunctions of the quantum states of neutrons in the potential well formed by the Earth's gravitational field and the horizontal mirror. The probability of finding neutrons at height z, corresponding to the nth quantum state, is proportional to the square of the neutron wavefunction $\psi_n^2(z)$. 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 the gravitational interaction for an object above a 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, or an atom, is extremely low; it is not equal to the surface temperature (the effective temperature of a particle in gravitational quantum states is ~10 nK)

A particle avobe a mirror in the gravity field: An ultracold neutron (V.I. Luschikov, A.I. Frank « Quantum effects occuring when ultracold neutrons are stored on a plane », JETP Lett. 28 (1978) 759) and … an anti-hydrogen atom (A.Yu. Voronin, P. Froelich, V.V. N. « Gravitational quantum states of antihydrogen », Phys. Rev. A 83 (2011) 032903) (a mirror represents a nearly infinitely-high and sharp potetial step)

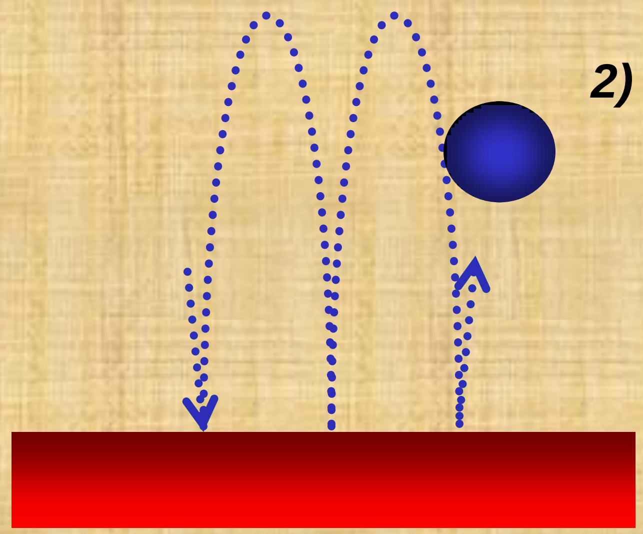
Energy of quantum states, in the Bohr-Zommerfeld approximation, equals :

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

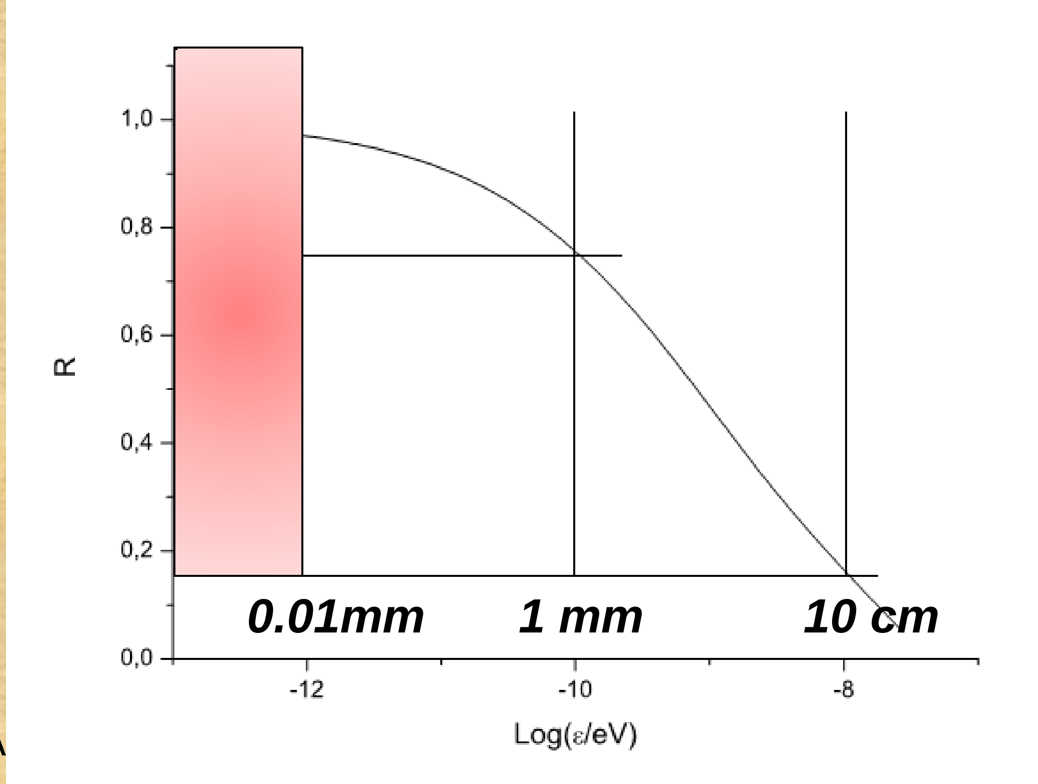
Choosing a quantum system

1) ***A neutron is reflected from the nuclear optical potential of a matter due to averaging of the neutron interaction with a huge number of nuclei***

2) ***An anti-matter (matter) atom is reflected from the sharply-changing (negative) van der Waals/ Casimir-Polder (vdW/CP) potential step (originating from vacuum fluctuations)*** *A.Yu. Voronin, P. Froelich, B. Zygelman, Phys. Rev. A 72 (2005) 062903*



A(n) (anti)-particle avobe a mirror in the gravity field



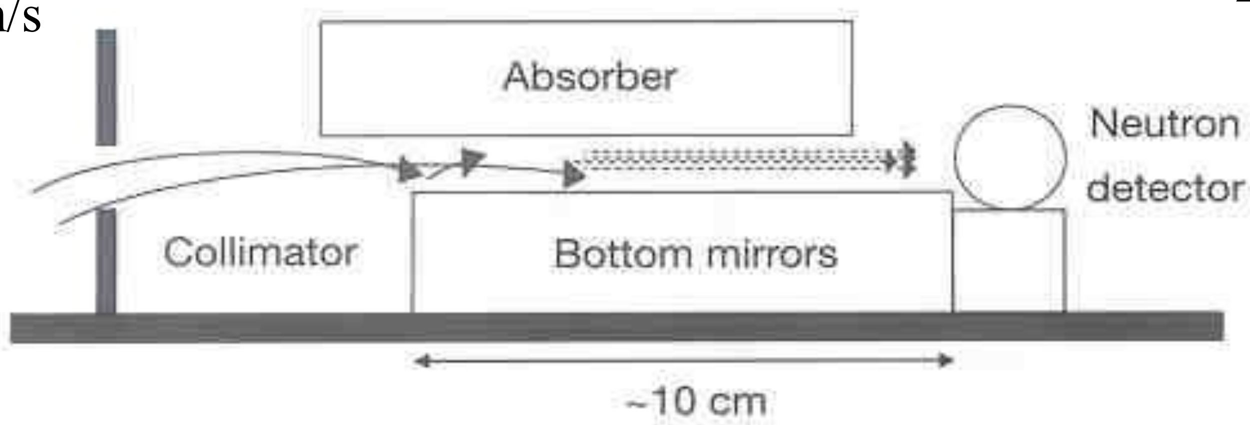
The experimental installation and the method used in the first neutron experiment

V.V. N., H.G. Borner, A.K. Petukhov, H. Abele, S. Baessler, F.J. Ruess, Th. Stoferle, A. Westphal, A.M. Gagarski, G.A. Petrov, A.V. Strelkov « Quantum states of neutrons in the Earth's gravitational field », Nature 415 (2002) 297; V.V. N., H.G. Boerner, A.M. Gagarski, A.K. Petukhov, G.A. Petrov, H. Abele, S. Baessler, G. Divcovic, F.J. Ruess, Th. Stoeferle, A. Westphal, A.V. Strelkov, K.V. Protasov, A.Yu. Voronin, « Measurement of quantum states of neutrons in the Earth's gravitational field », Phys. Rev. D 67 (2003) 102002.

V_{horiz}~4-15 m/s

V_{vert}~2 cm/s

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



Selection and measurement of the vertical and horizontal velocity components:

The maximum vertical velocity is defined by the scatterer/absorber height above the mirror

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

The experimental installation and the method
Model of tunneling through a gravitational barrier

V.V. N., A.K. Petukhov, H.G. Boerner, T.A. Baranova, A.M. Gagarski, G.A. Petrov, K.V. Protasov, A.Yu. Voronin, S. Baessler, H. Abele, A. Westphal, L. Lucovac, « Study of the neutron quantum states in the gravity field », Europ. Phys. J. C 40 (2005) 479; A. Yu. Voronin, H. Abele, S. Baessler, V.V. Nesvizhevsky, A.K. Petukhov, K.V. Protasov, A. Westphal, « Quantum motion of a neutron in a waveguide in the gravitational field », Phys. Rev. D 73 (2006) 044029.

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

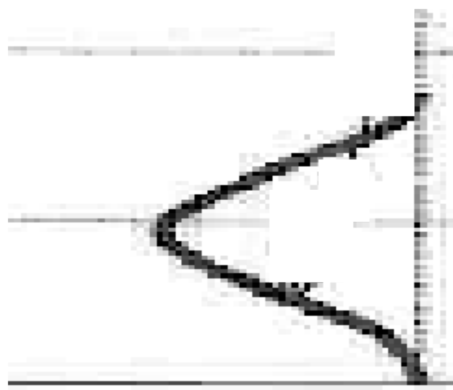
$$D(\xi) \approx Exp[-\frac{4}{3} \cdot \xi^{\frac{3}{2}}],$$

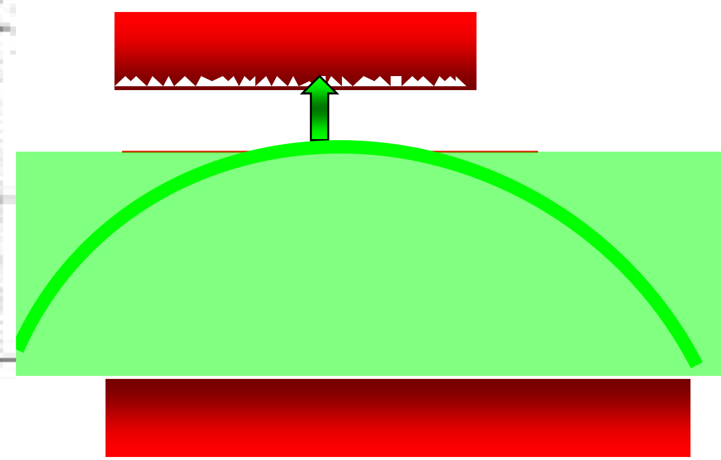
$$P_n(\xi) = Exp(-\Gamma_n(\xi) \cdot \tau)$$

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

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

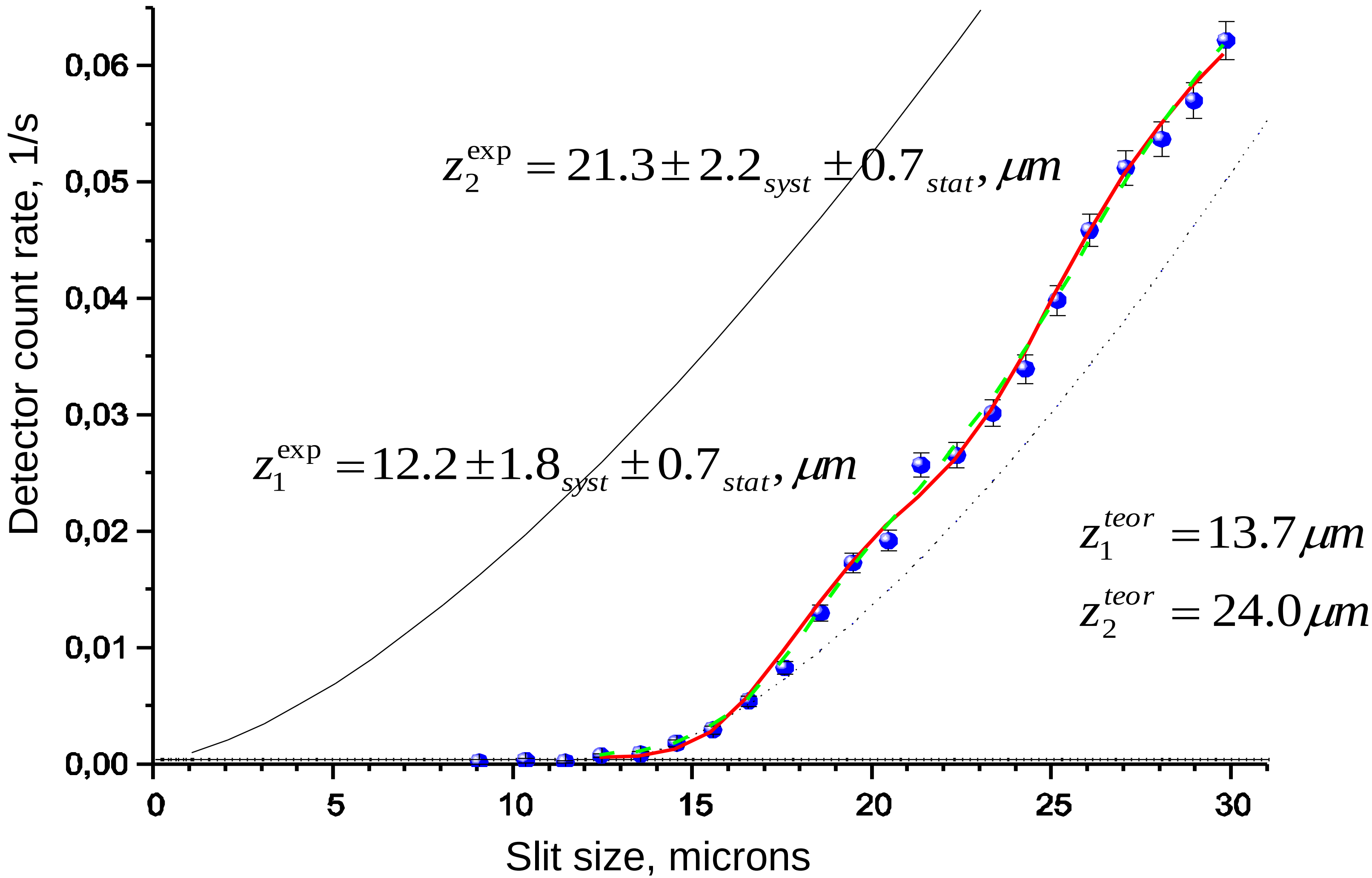
$$P_n(\xi) = Exp(-\Gamma_n(\xi) \cdot \frac{L}{V_{hor}})$$





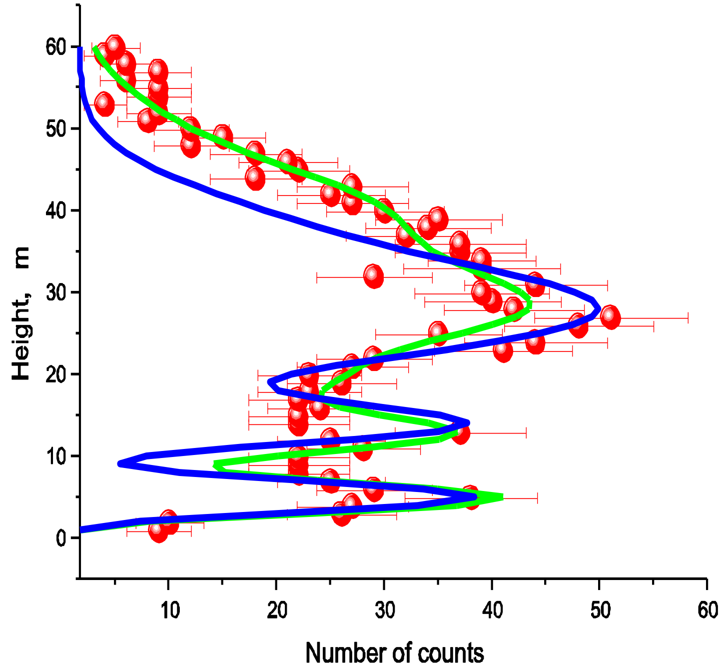
« Integral » method; soft spectrum

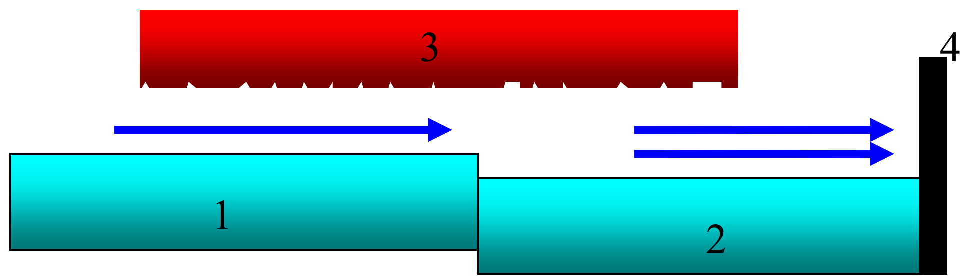
V.V. N., A.K. Petukhov, H.G. Boerner, T.A. Baranova, A.M. Gagarski, G.A. Petrov, K.V. Protasov, A.Yu. Voronin, S. Baessler, H. Abele, A. Westphal, L. Lucovac, « Study of the neutron quantum states in the gravity field », Europ. Phys. J. C 40 (2005) 479.



« Differential » method, position-sensitive detectors

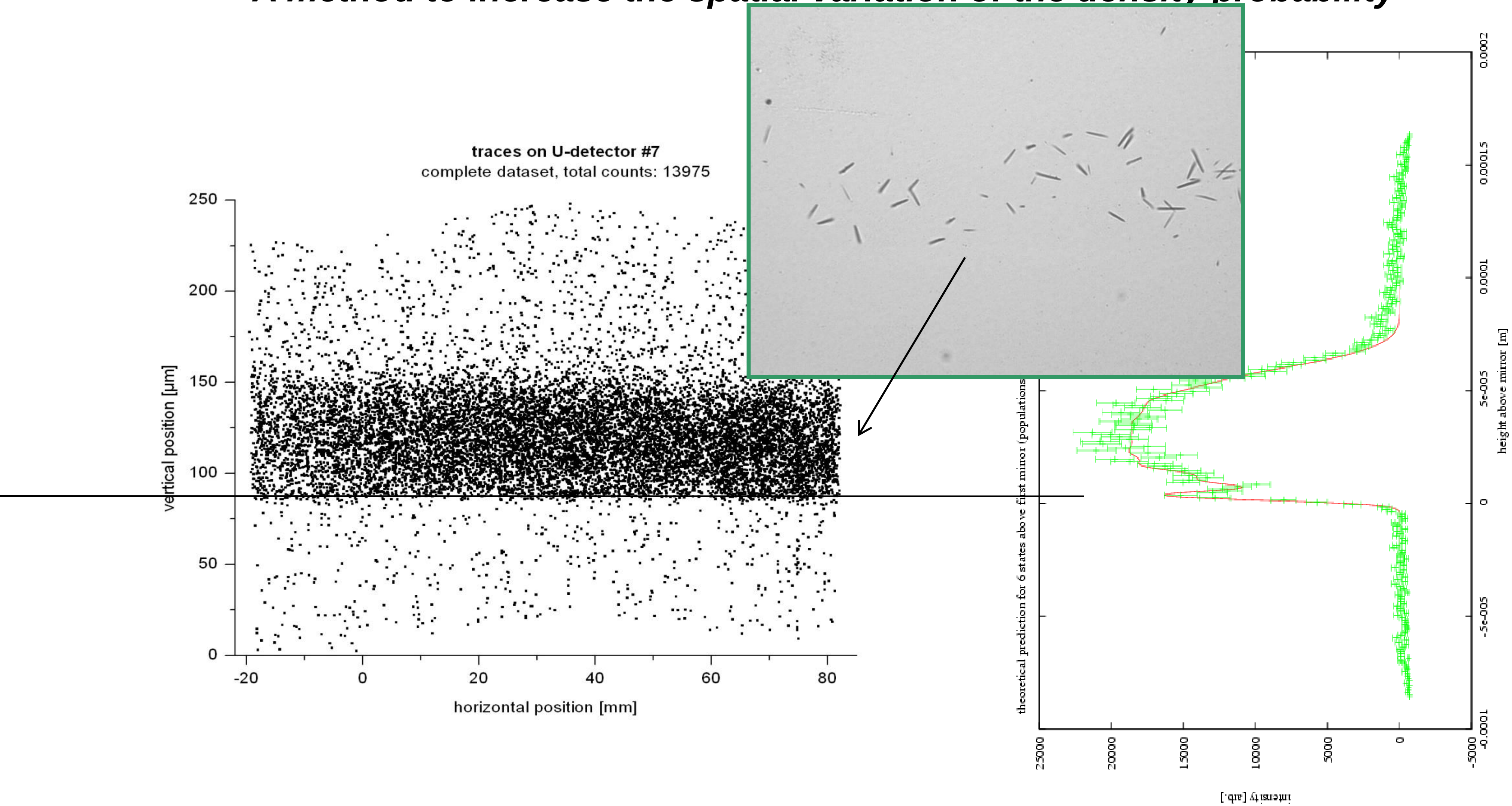
A method to increase the spatial variation of the density probability





« Differential » method, position-sensitive detectors

A method to increase the spatial variation of the density probability



Transitions between gravitational quantum states

Remember: flow-through mode; modest energy resolution

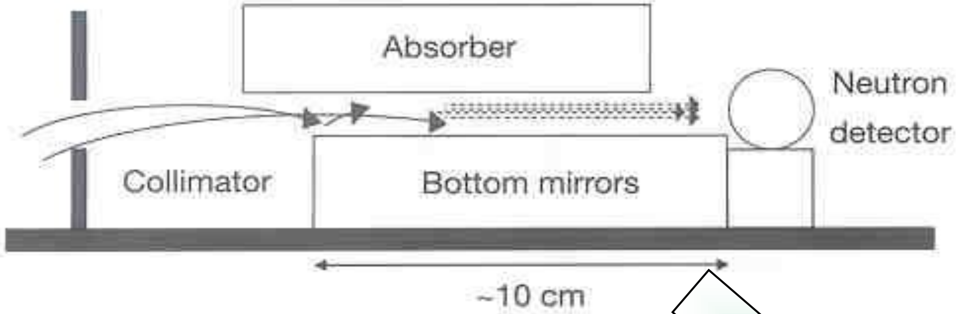


Figure 2 Layout of the experiment. The limitation of the vertica[illegible] component depends on the relative position of the absorber and mirror. To limit th[illegible]ntal velocity component we use an additional entry collimator. The relative height and [illegible] the entry collimator can be adjusted.

Transitions could be excited, for instance:

- By periodically varying magnetic field gradient;

-By periodically varying local gravitational field;

-By oscillating mechanically the mirror

V.V. N., K.V. Protasov, « Quantum states of neutrons in the Earth's gravitational field : state of the art, applications, perspectives », Ed. Book on Trends in Quantum Gravity Research (NOVA science publishers, New York, 2006).

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

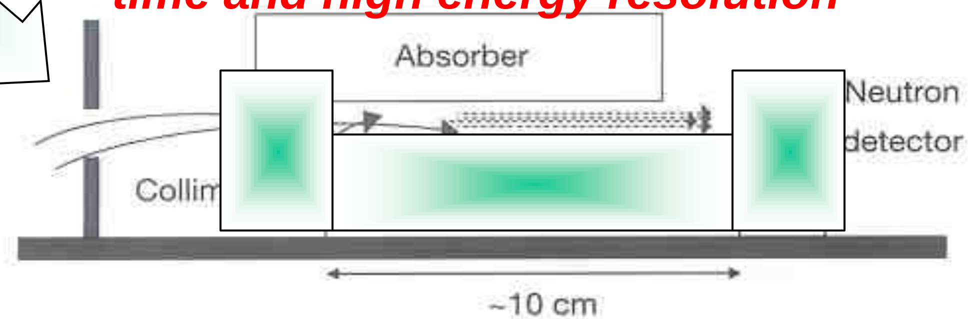
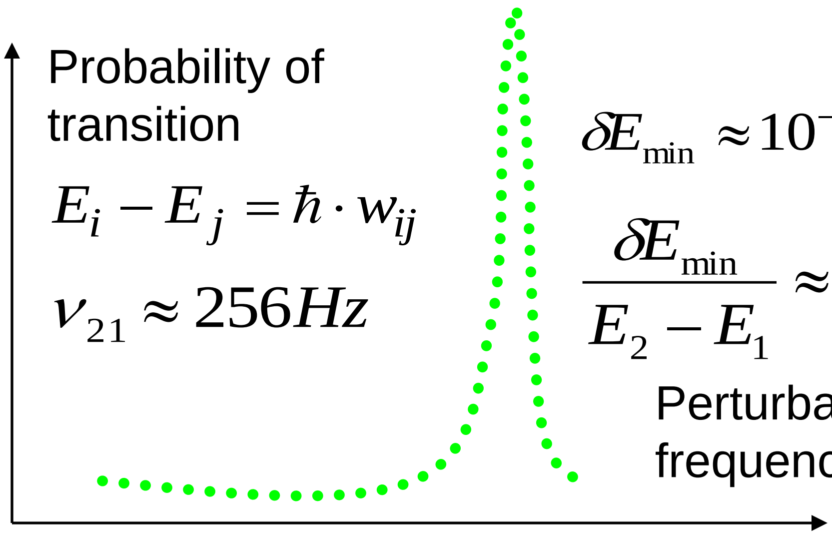


Figure 2 Layout of the experiment. The limitation of the vertical velocity component depends on the relative position of the absorber and mirror. To limit the horizontal velocity component we use an additional entry collimator. The relative height and size of the entry collimator can be adjusted.



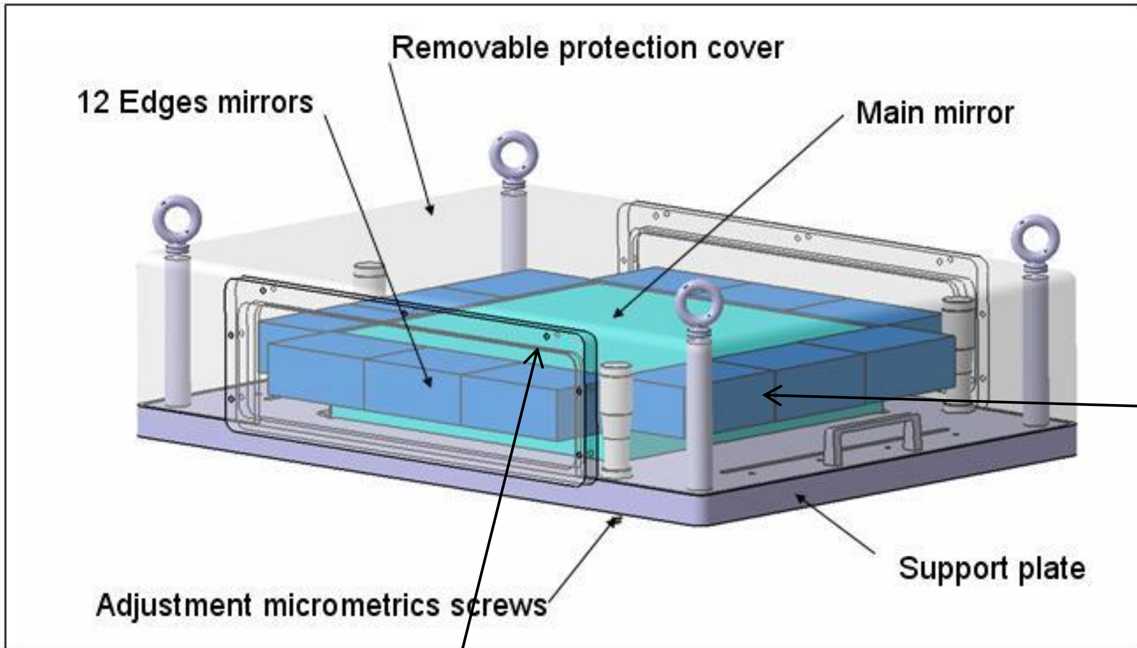
$$E_i - E_j = \hbar \cdot w_{ij}$$

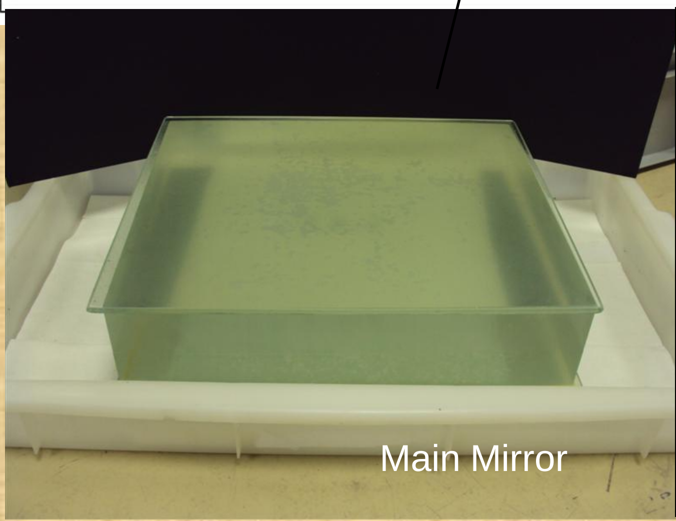
$$\nu_{21} \approx 256 Hz$$

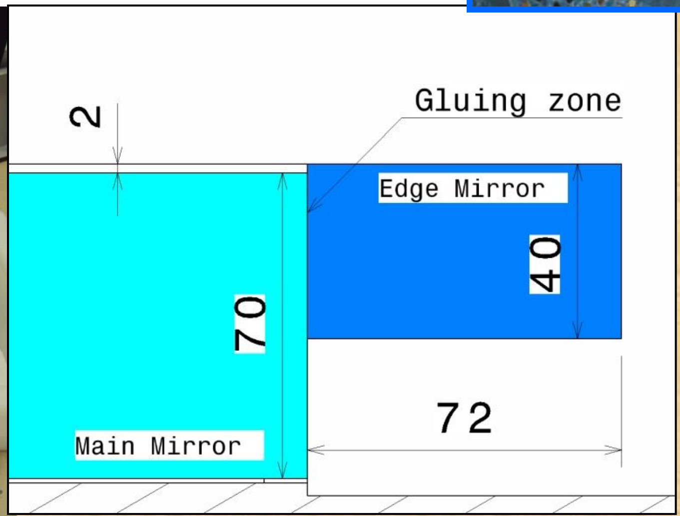
$$\delta E_{\min} \approx 10^{-18} eV$$

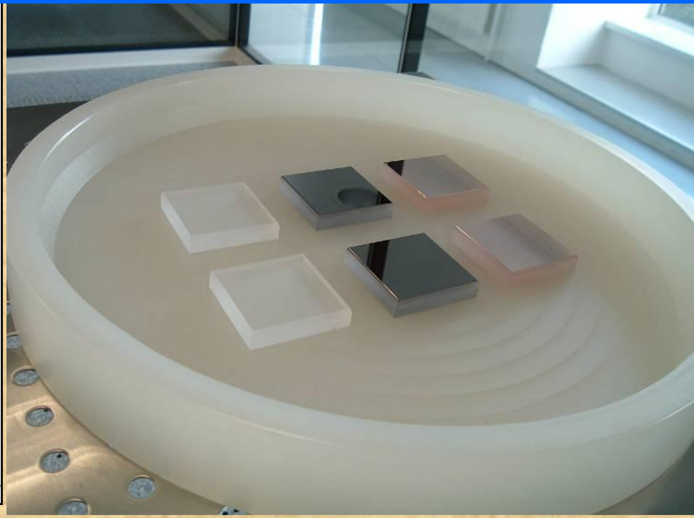
$$\frac{\delta E_{\min}}{E_2 - E_1} \approx 10^{-6}$$

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

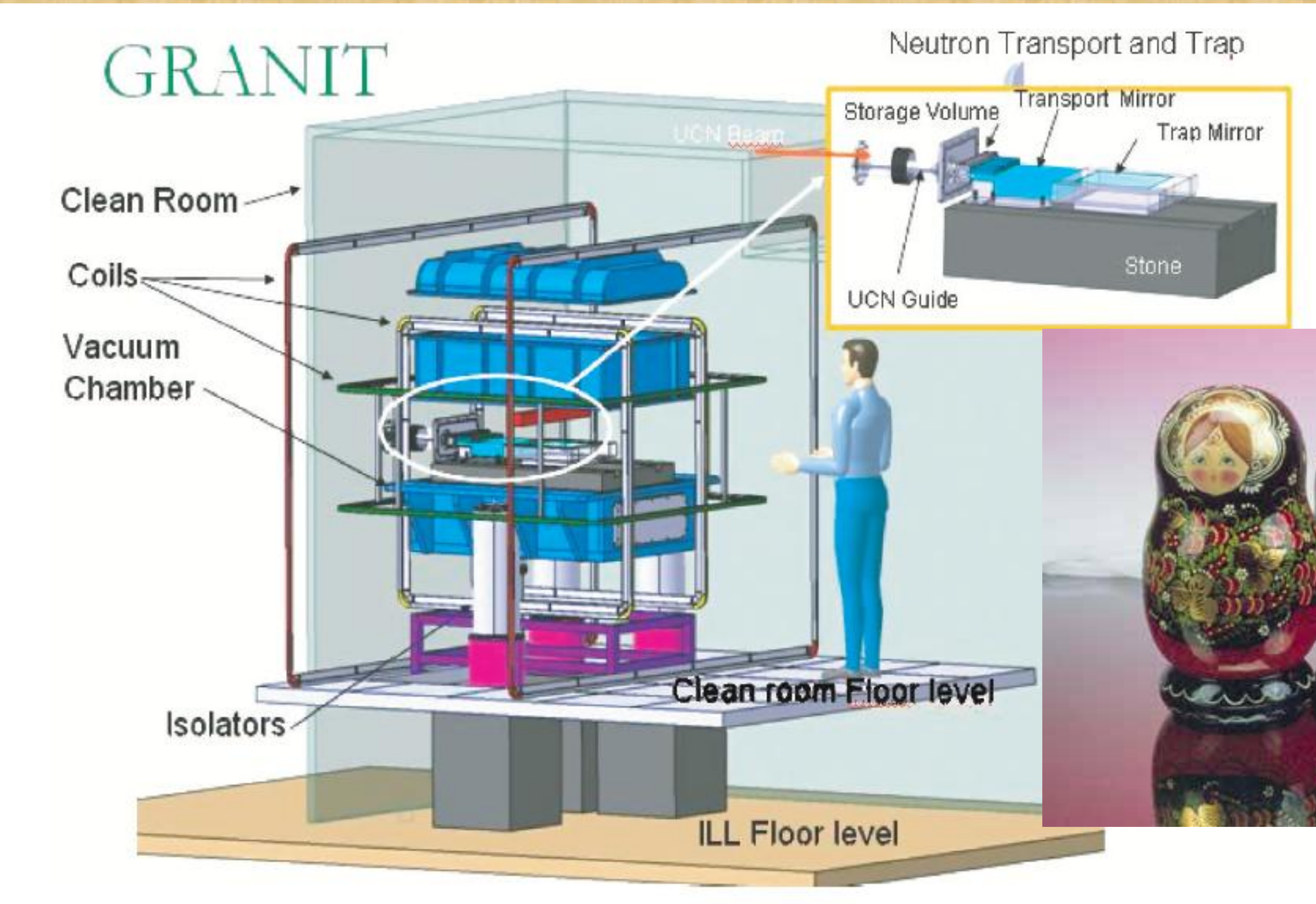


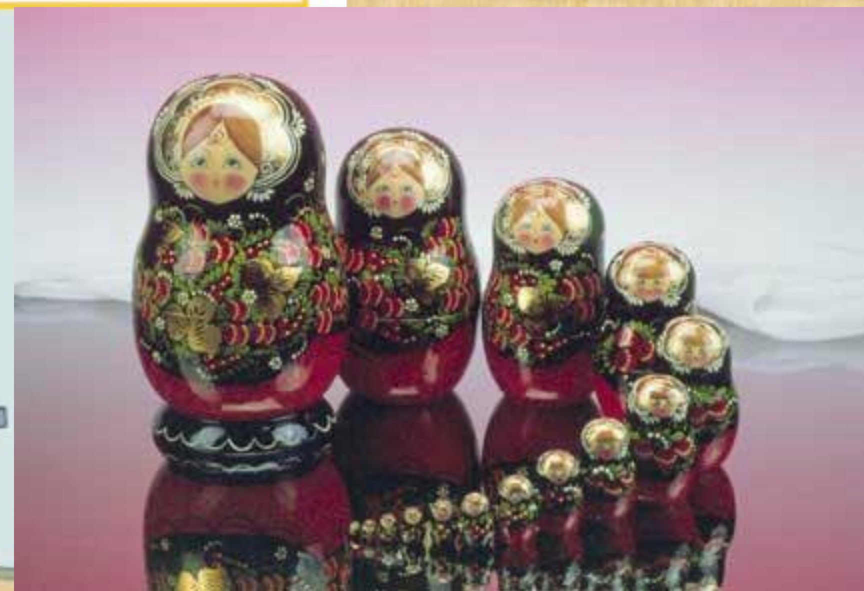




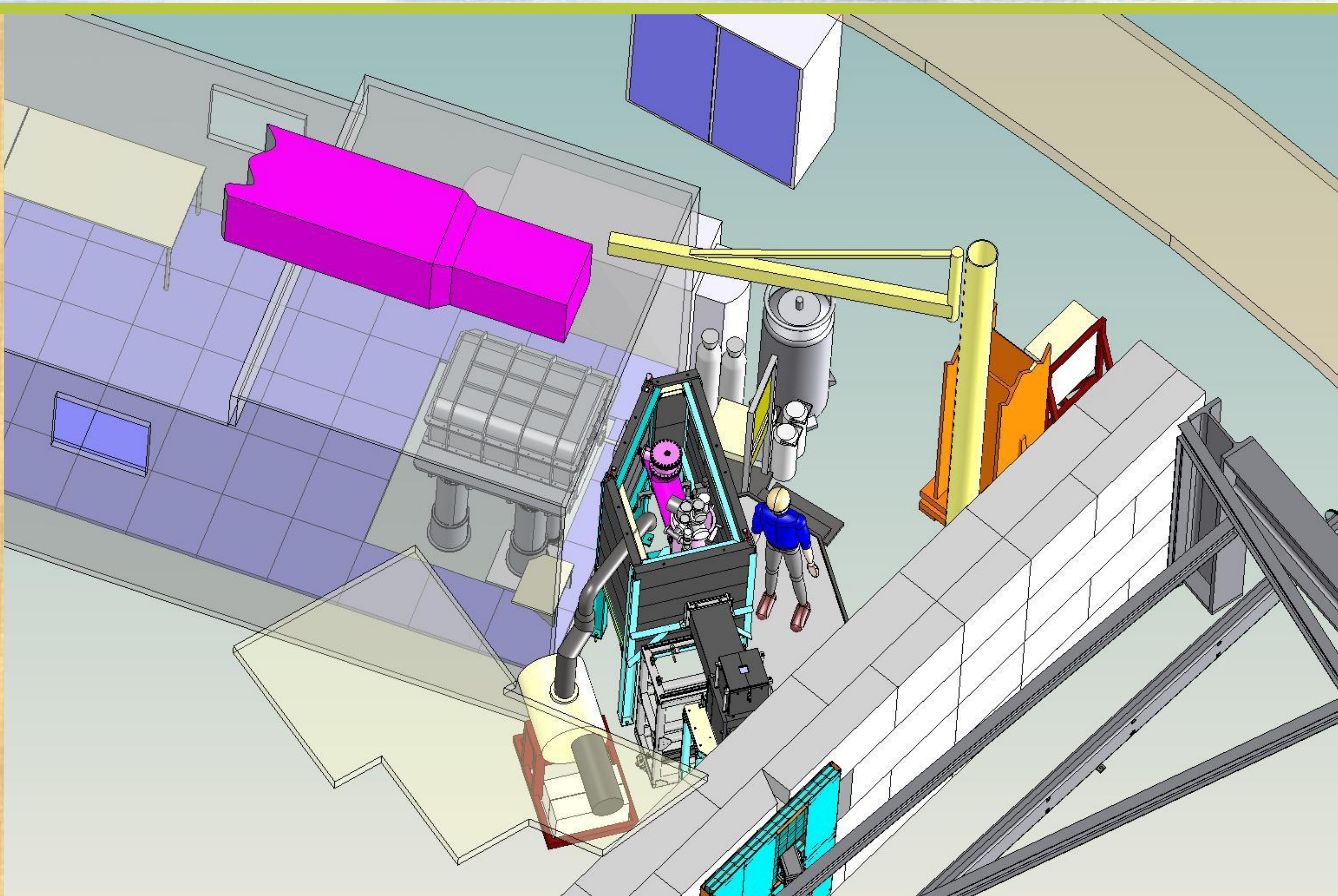


GRANIT
Assembling the spectrometer

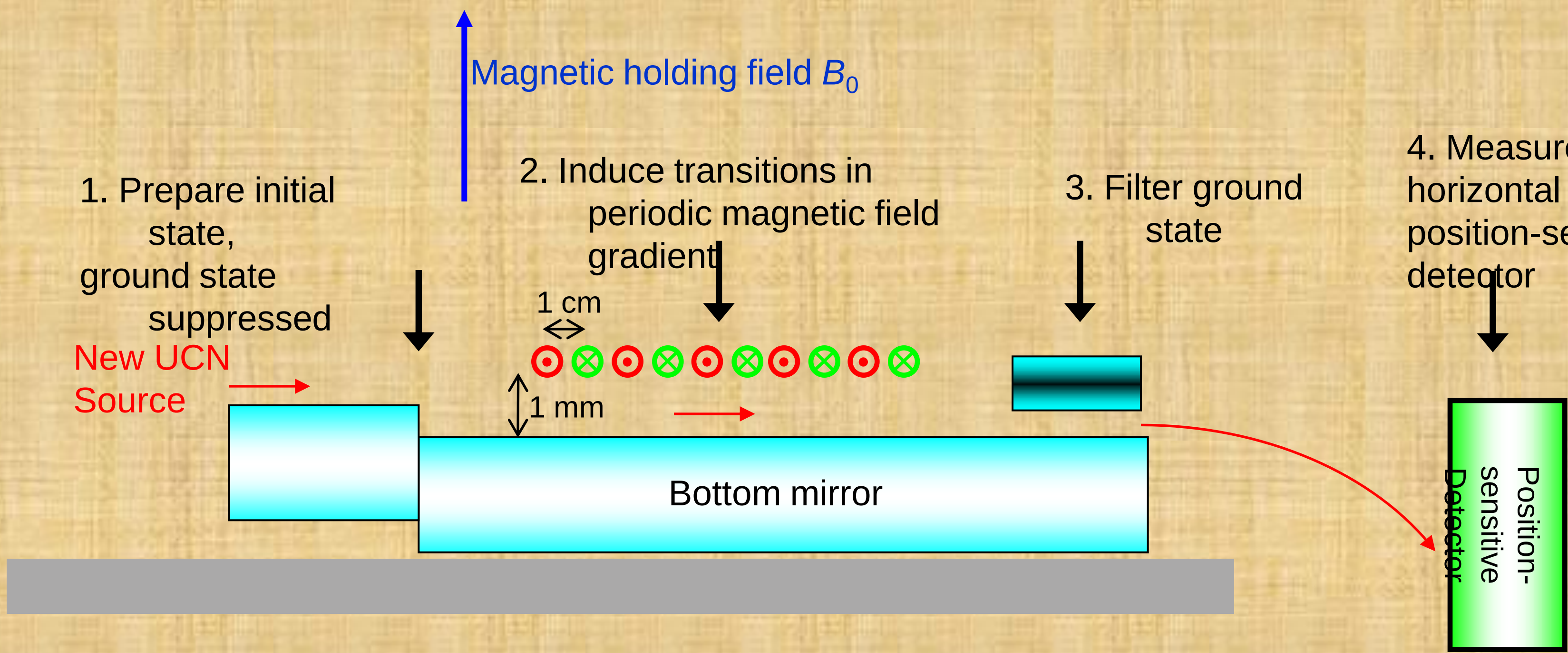


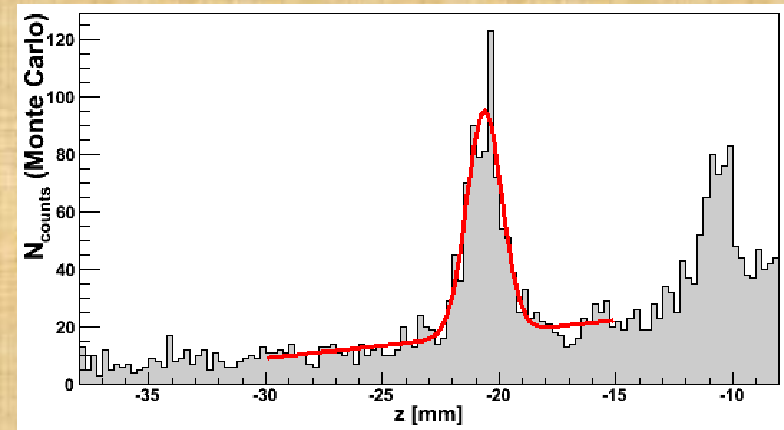


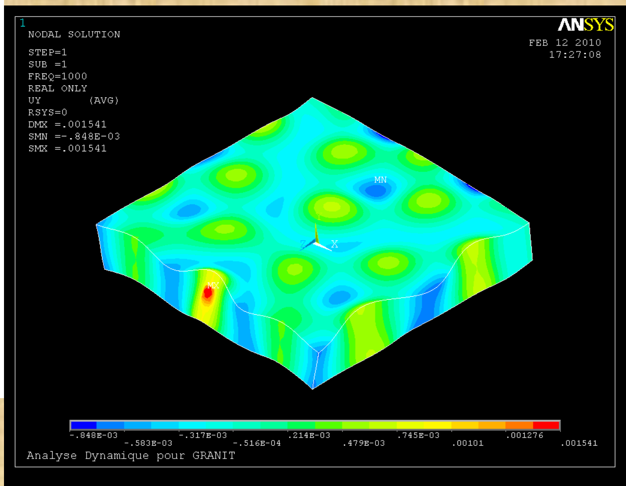
Installation of GRANIT spectrometer at the level C at ILL

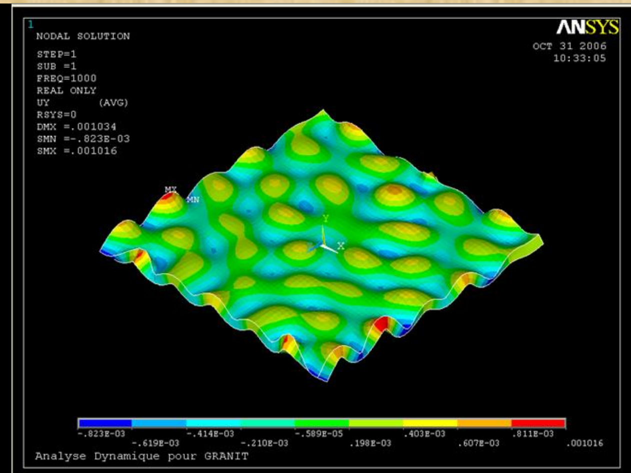


GRANIT
on methods of excitation the transitions









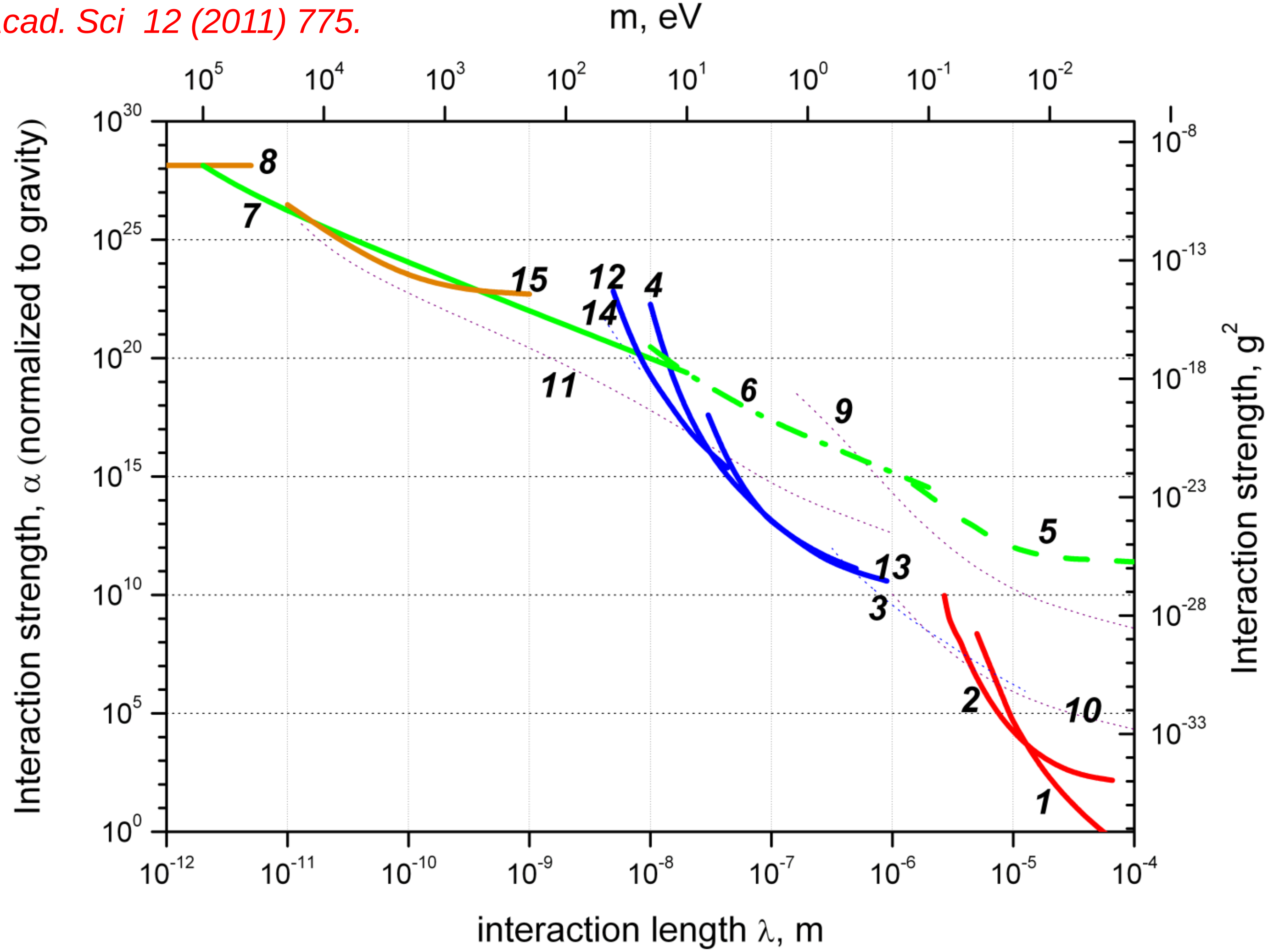
Applications

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 effects;***
-***UCN reflectometry;***
-***Quantum revivals;***
-***Constrains for a logarithmic term in the Schrödinger equation;***
-***Loss of quantum coherence;***
-***UCN extraction, transport, tight valves;***
-Study of thin surface layers;
-etc....

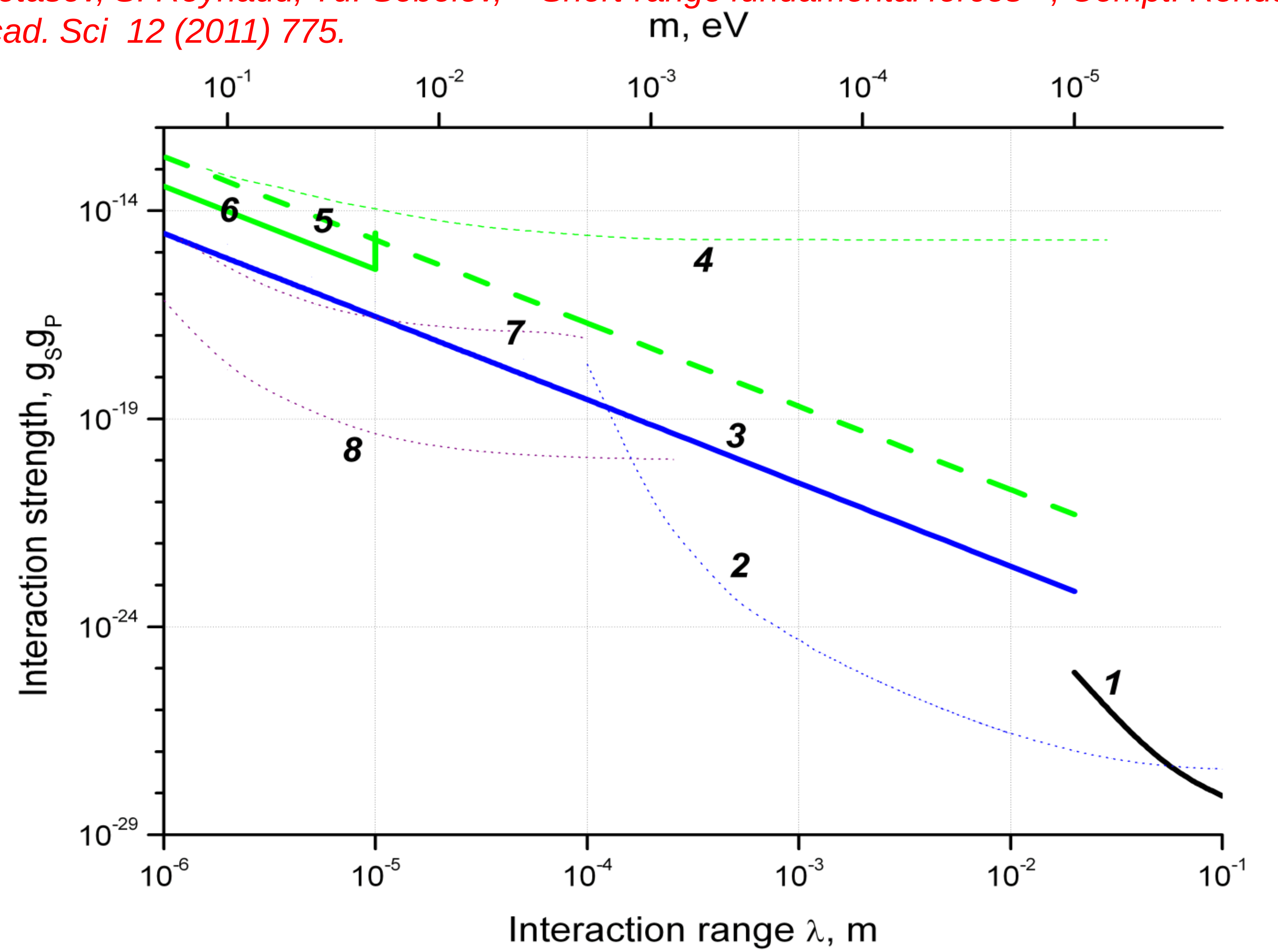
Constrains for short-range forces

I. Antoniadis, S. Baessler, M. Buchner, V.V. Fedorov, S. Hoedl, V.V. N., G. Pignol, K.V. Protasov, S. Reynaud, Yu. Sobolev, « Short-range fundamental forces », Compt. Rendu Acad. Sci 12 (2011) 775.



Constrains for short-range forces

I. Antoniadis, S. Baessler, M. Buchner, V.V. Fedorov, S. Hoedl, V.V. N., G. Pignol, K.V. Protasov, S. Reynaud, Yu. Sobolev, « Short-range fundamental forces », Compt. Rendu Acad. Sci 12 (2011) 775.



Numerous follow-up projects and technical developments to study and use gravitational quantum states of neutrons

T. Sanuki, S. Komamiya, S. Kawasaki, S. Sonoda, « Proposal for measuring the quantum states of neutrons in the gravitational field with a CCD-based pixel sensor », NIM A 600 (2009) 657.

J. Jakubek, Ph. Schmidt-Wellenburg, P. Geltenbort, M. Platkevic, Ch. Plonka-Spehr, J. Solc, T. Soldner, « A coated pixel device TimPix with micron spatial resolution for UCN detection », NIM A 600 (2009) 651.

J. Jakubek, M. Platkevic, Ph. Schmidt-Wellenburg, P. Geltenbort, Ch. Plonka-Spehr, M. Daum, « Position-sensitive spectroscopy of ultra-cold neutrons with Timepix pixel detector », NIM A 607 (2009) 45.

H. Abele, T. Jenke, D. Stadler, P. Geltenbort, « QuBounce: the dynamics of ultracold neutrons falling in the gravity potential of the Earth », Nucl. Phys. A 827 (2009) 593.

T. Jenke, T. Stadler, H. Abele, P. Geltenbort, « Q-Bounce-experiments with quantum bouncing ultracold neutrons », NIM A 611 (2009) 318.

S. Kawasaki, G. Ichikawa, M. Hino, Y. Kamiya, M. Kitaguchi, S. Komamiya, T. Sanuki, S. Sonoda, « Development of a pixel detector for ultracold neutrons », NIM A 615 (2010) 42.

T. Jenke, P. Geltenbort, H. Lemmel, H. Abele, « Realization of a gravity-resonance-spectroscopy technique », Nature Phys. 7 (2011) 468.

Feasibility of analogous experiments with anti-hydrogen

NEUTRONS FOR SCIENCE

A.Yu. Voronin, P. Froelich, V.V. N. « Gravitational quantum states of antihydrogen », Phys. Rev. A 83 (2011) 032903

Similarities:

1. The anti-hydrogen mass is about equal to the neutron mass

2. Modifications, due to the vdW/CP potential, of the anti-hydrogen quantum states energies and wave-functions are negigible

3. Lifetimes of anti-hydrogen in quantum states are at least ~0.1 s, that is even longer than the time of UCN passage through the setup used for the first neutron experiment

4. Projected anti-hydrogen velocities are even smaller than typical UCN velocities.

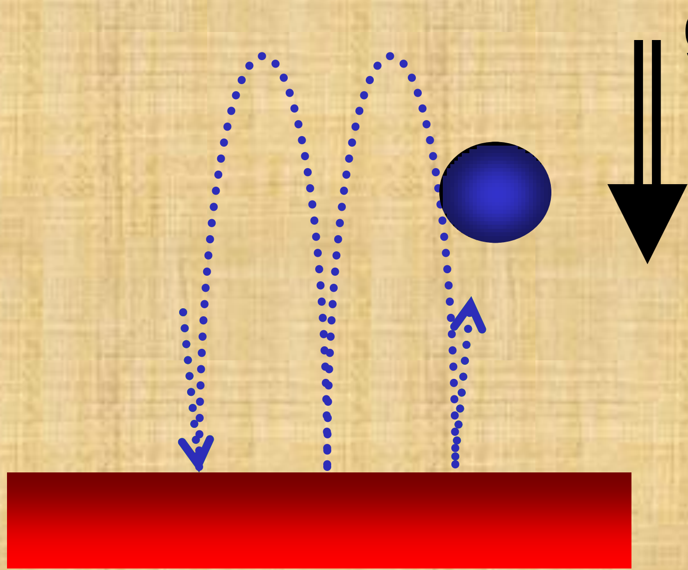
5. Projected anti-hydrogen phase-space densities are even larger than the highest UCN densities available.

6. But: effects of parasitic electromagnetic fields to anti-hydrogen atoms are much larger than those to neutrons! Should not be overlooked, but looks promissing.

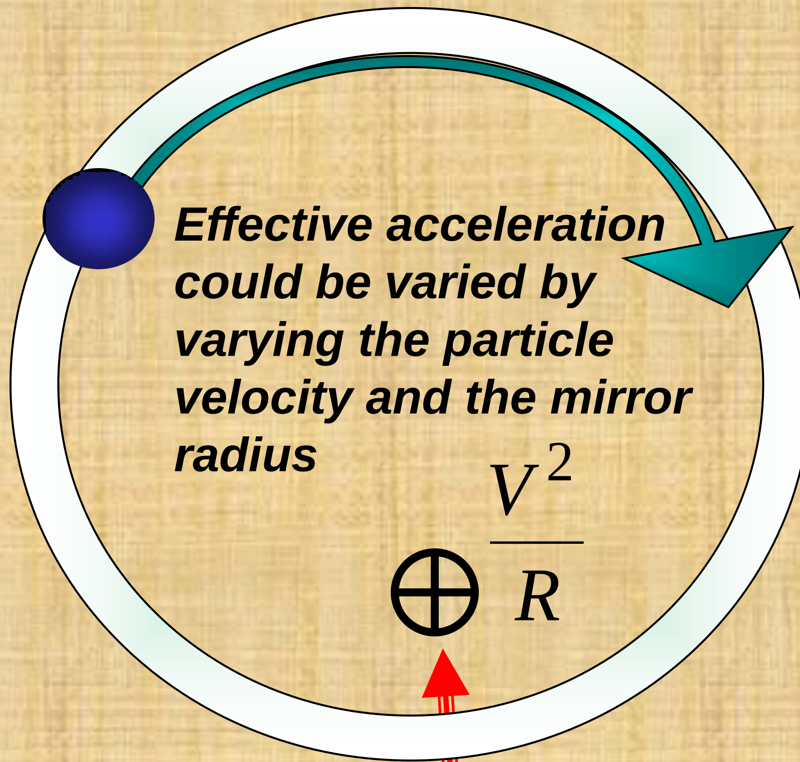
Conclusion (on gravitational quantum states)

1. First observation of quantum states of UCN in the gravitational field above a mirror; first demonstration (and still the only one!) of quantum states of matter in a gravitational field
2. Applications in fundamental and surface physics
3. New gravitational spectrometer GRANIT, with all parameters largely improved compared to the first setup, is going to become operational this year
4. Such an experiment is feasible with anti-hydrogen
5. The GRANIT spectrometer could be used for one-to-one prototyping of an experiment measuring quantum states of anti-hydrogen atoms

Gravity / Acceleration



A particle above a mirror in the gravity field



The energy of quantum states in the Bohr-Zommerfeld approximation :

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

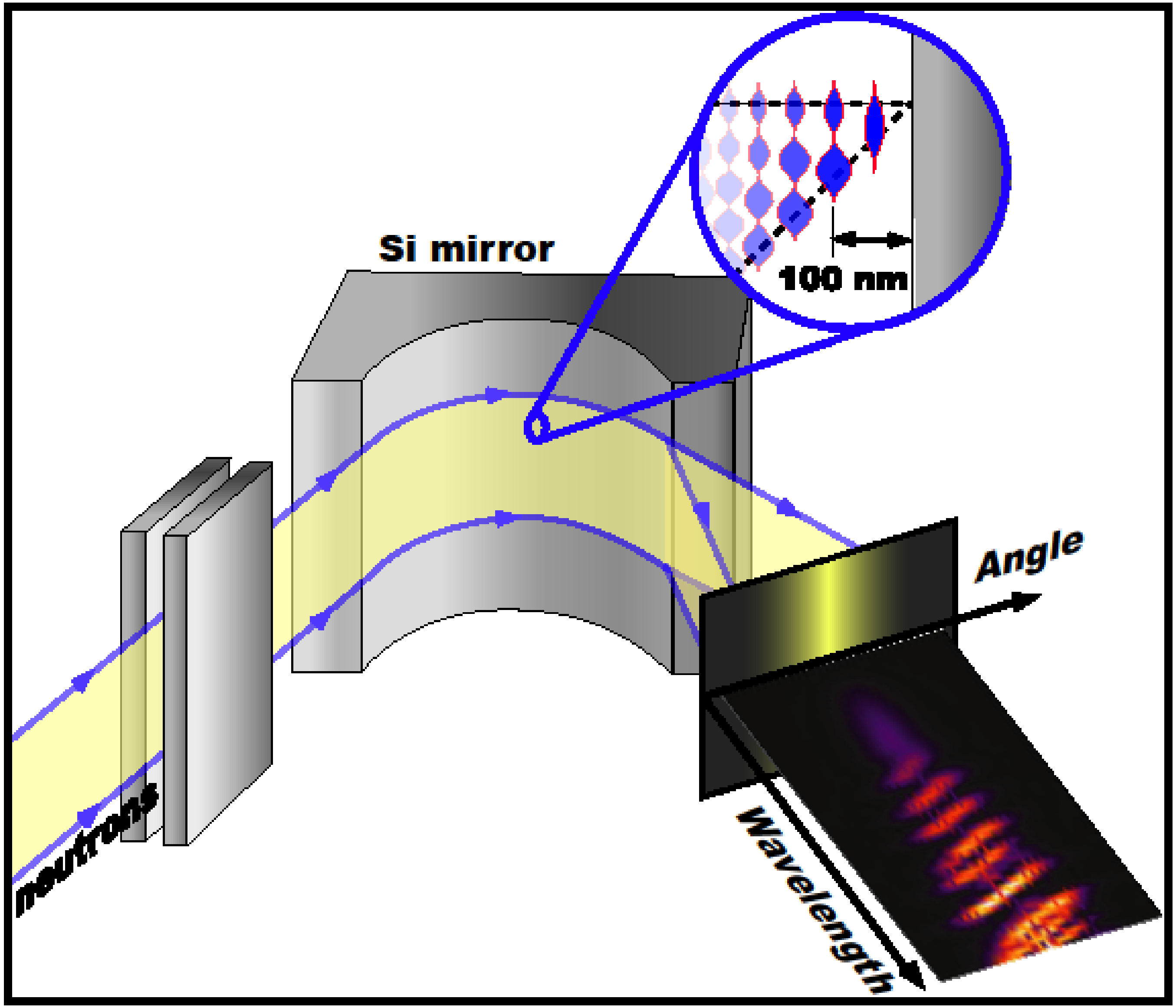
Neutron whispering gallery

V.V. N., A.K. Petukhov, K.V. Protasov, A.Yu. Voronin, «Centrifugal quantum states of neutrons », Phys. Rev. A 78 (2008) 033616;

R. Cubitt, V.V. N., A.K. Petukhov, A.Yu. Voronin, G. Pignol, K.V. Protasov, « Methods of observation of the centrifugal quantum states of neutrons », NIM A 611 (2009) 322;

V.V. N., A.Yu. Voronin, R. Cubitt, K.V. Protasov, « Neutron whispering gallery », Nature Physi. 6 (2010) 114;

V.V. N., R. Cubitt, K.V. Protasov, A.Yu. Voronin, « The whispering gallery effect in neutron scattering », New J. Phys. 6 (2010) 113050.



Neutron whispering gallery

nature physics

LETTERS

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

Neutron whispering gallery

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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

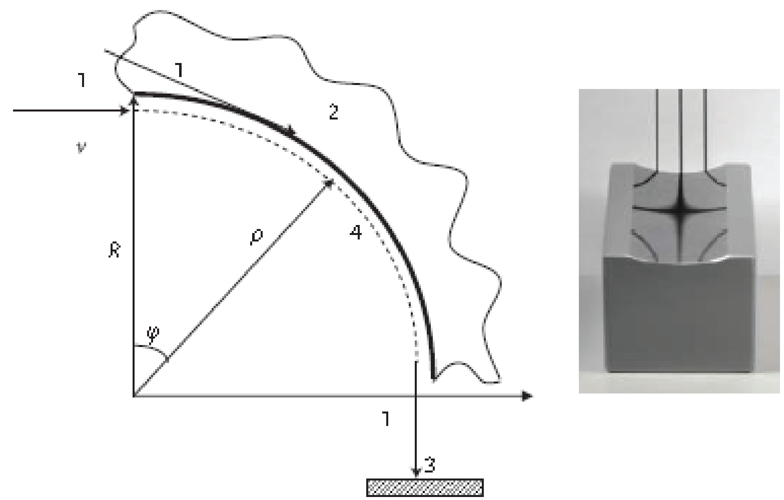


Figure 1 | A scheme of the neutron centrifugal experiment. 1: Classical trajectories of incoming and outgoing neutrons, 2: cylindrical mirror, 3: neutron detector, 4: quantum motion along the mirror surface. Inset: A photo of the single-crystal cylindrical silicon mirror used for the presented experiments,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

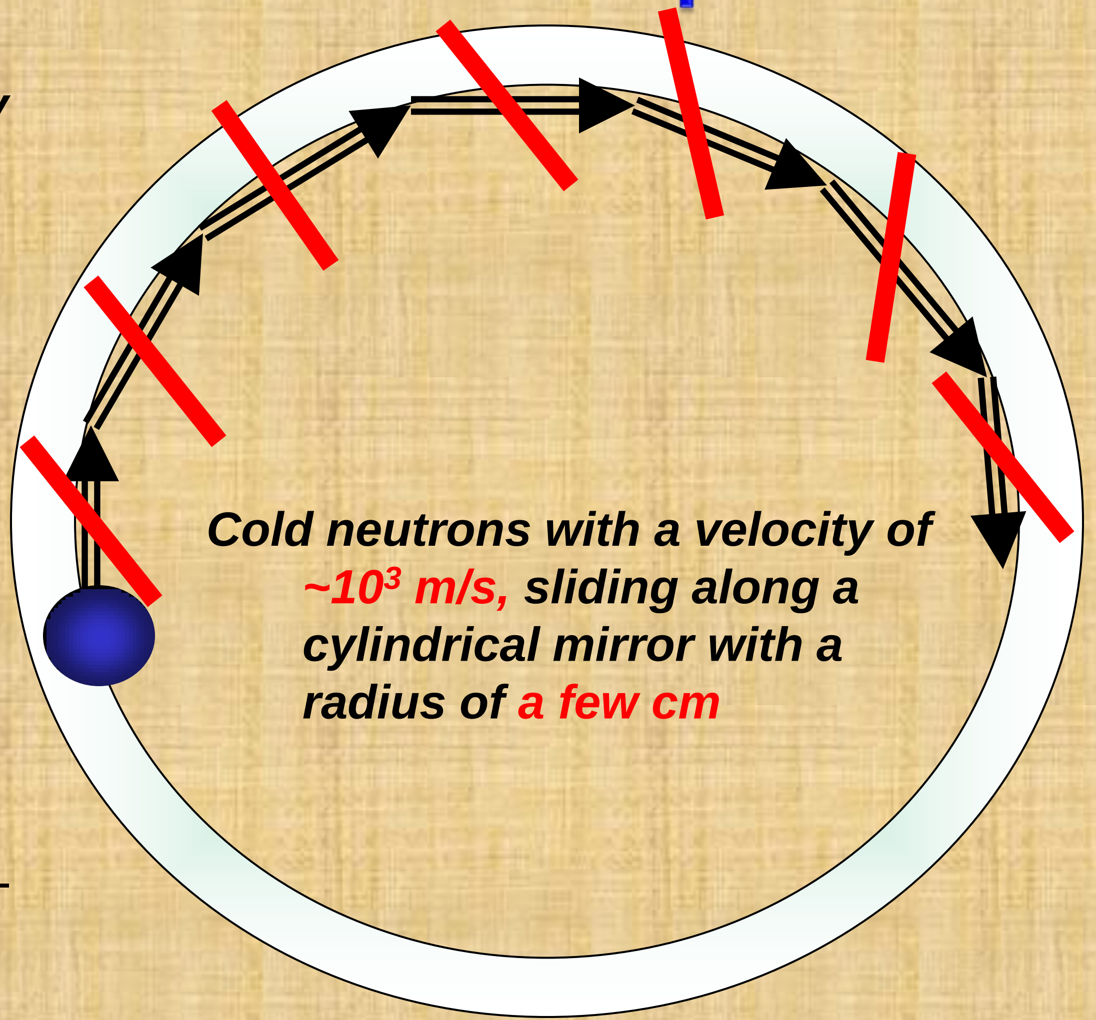
Neutron whispering gallery

Massive particle, sliding along a 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:

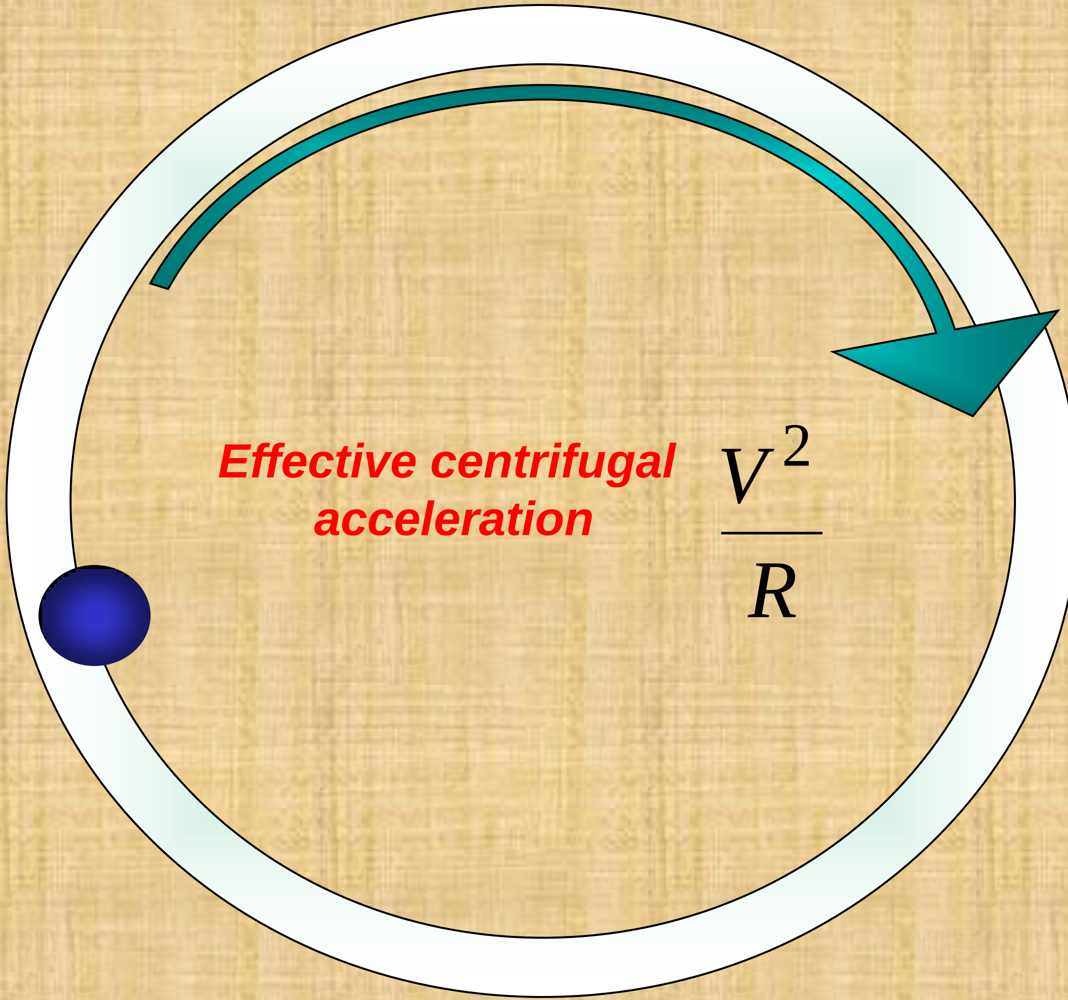
- Mabuchi H. & Kimble H.J. Atom galleries for whispering atoms – binding atoms in stable orbits around an optical resonator. *Opt. Lett*. **19**, 749-751 (1994).
- Vernooy D. M. & Kimble H.J. Quantum structure and dynamics for atom galleries. *Phys. Rev. A* **55**, 1239-1261 (1997).

Characteristic parameters



Two « independent » velocity components

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

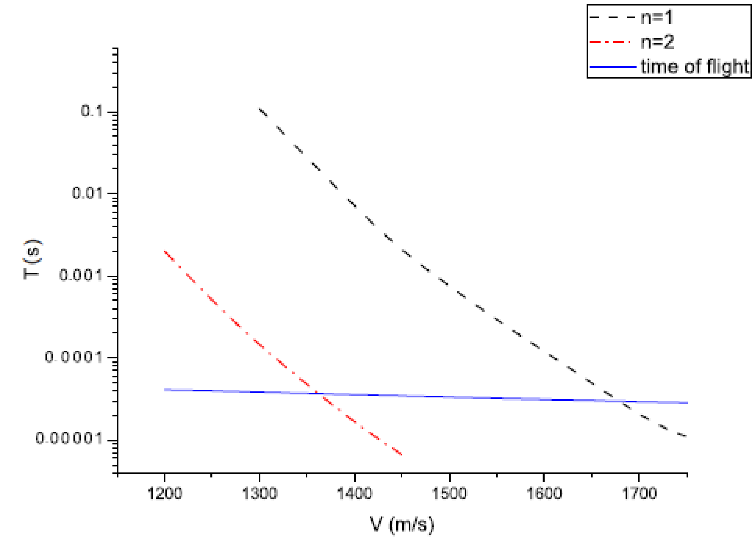


$$\frac{V^2}{R}$$

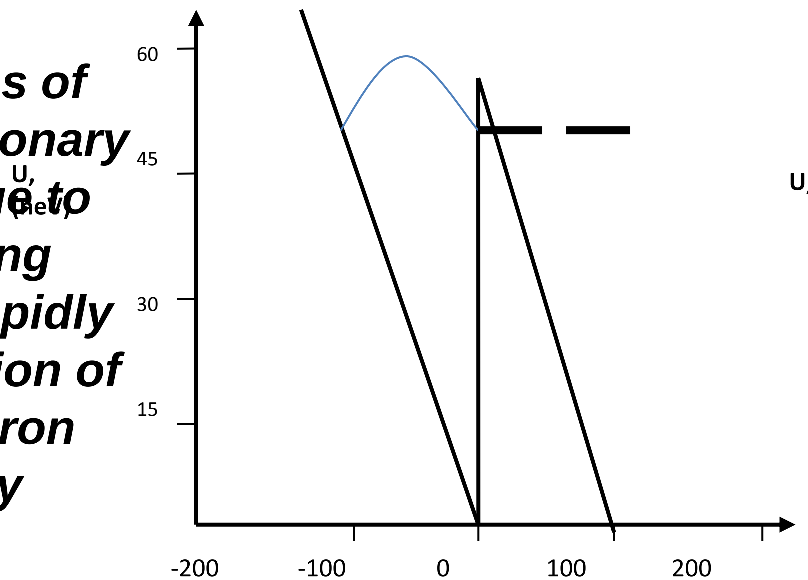
Methods of observation

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

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

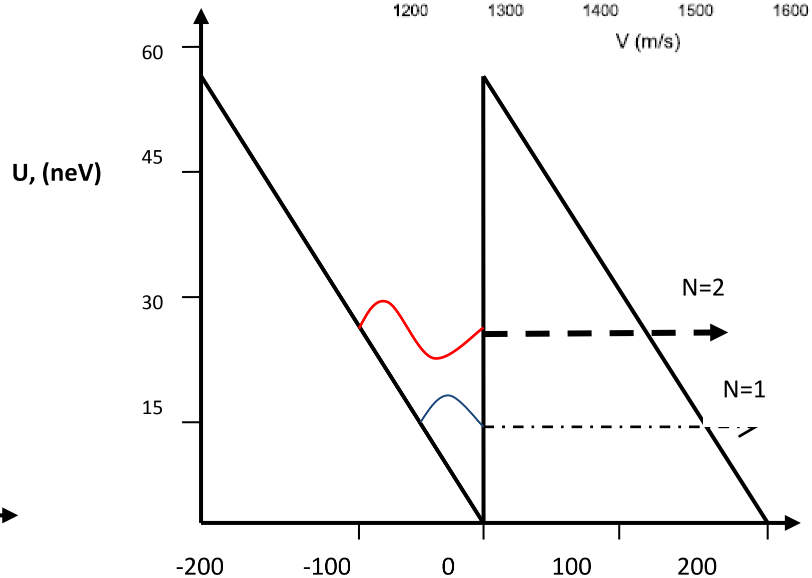


Life-times of quasi-stationary states due to tunneling change rapidly as a function of the neutron energy



R-ρ, (nm)

λc

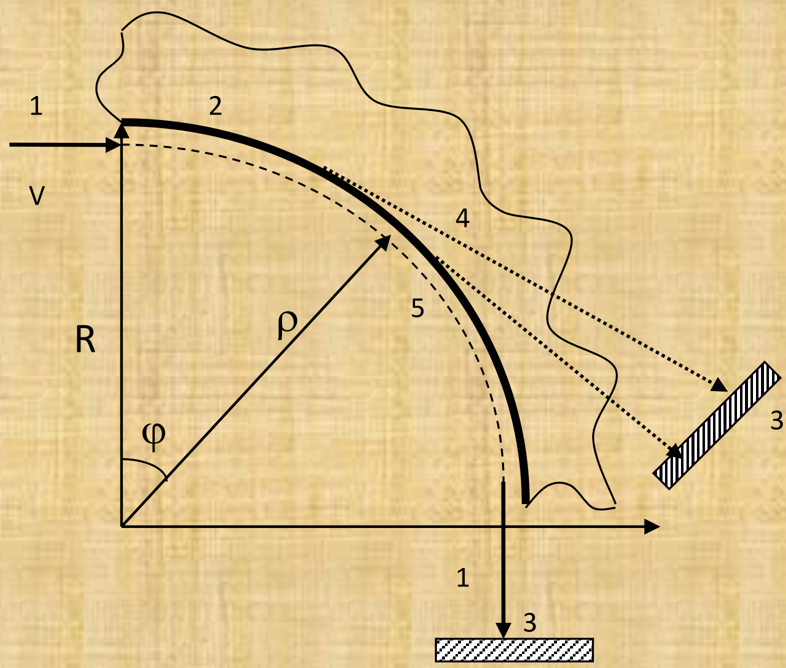


R-ρ, (nm)

λ>λc

Tunneling

Methods of observation

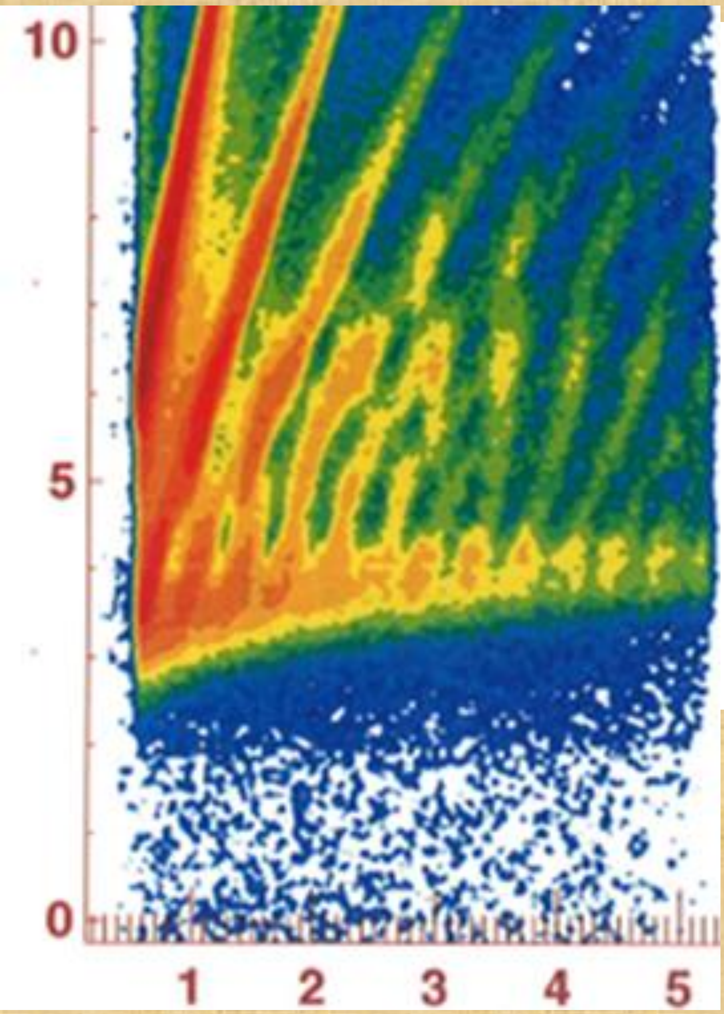


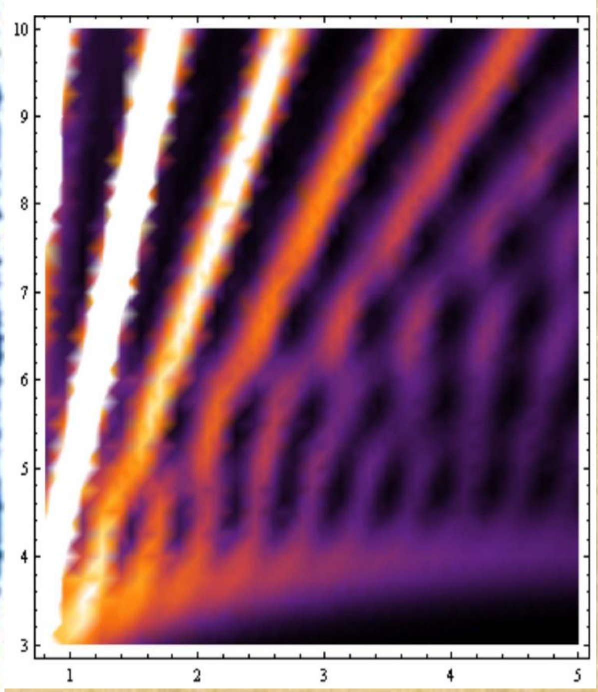
Neutrons entering from edge of a truncated cylindrical mirror

D17 instrument at the ILL

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

Results: NEUTRON RAINBOW



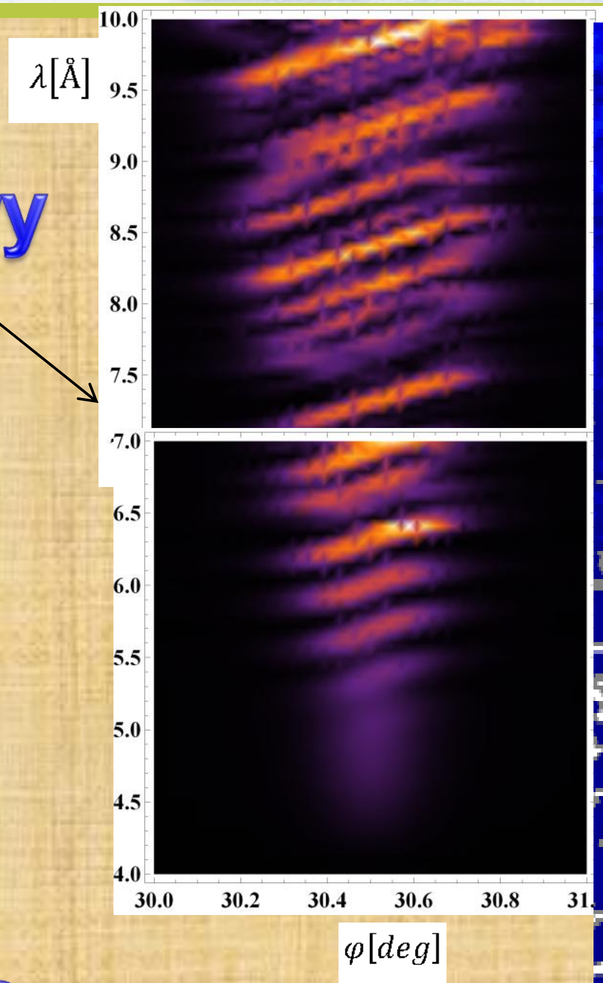


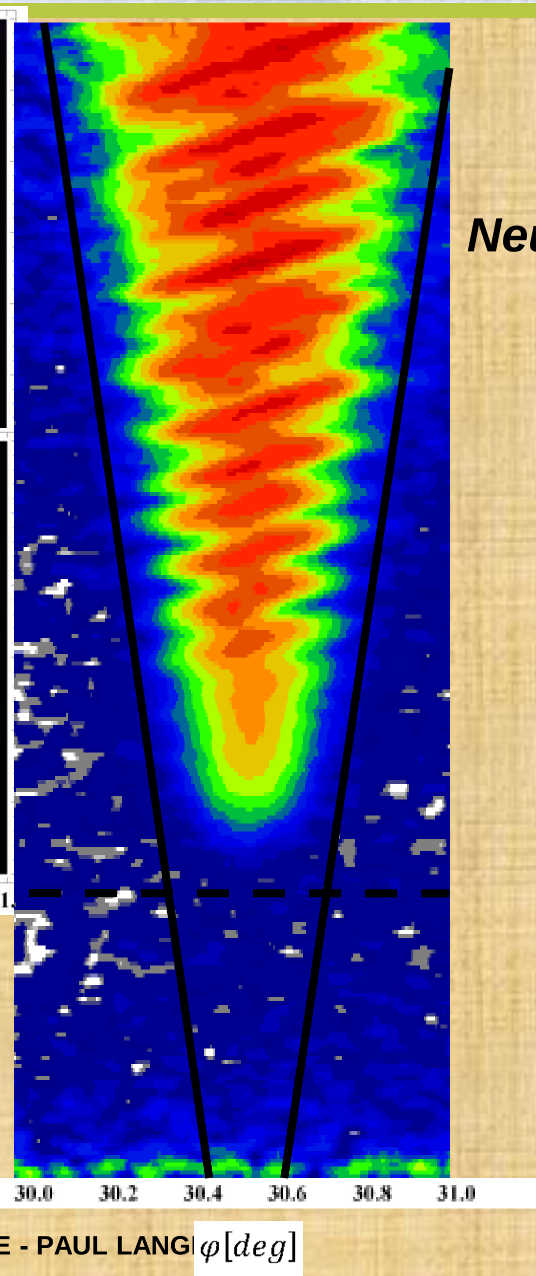
Neutrons tunneling OUT of quantum states

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

Results: NEUTRON RAINBOW

Theory



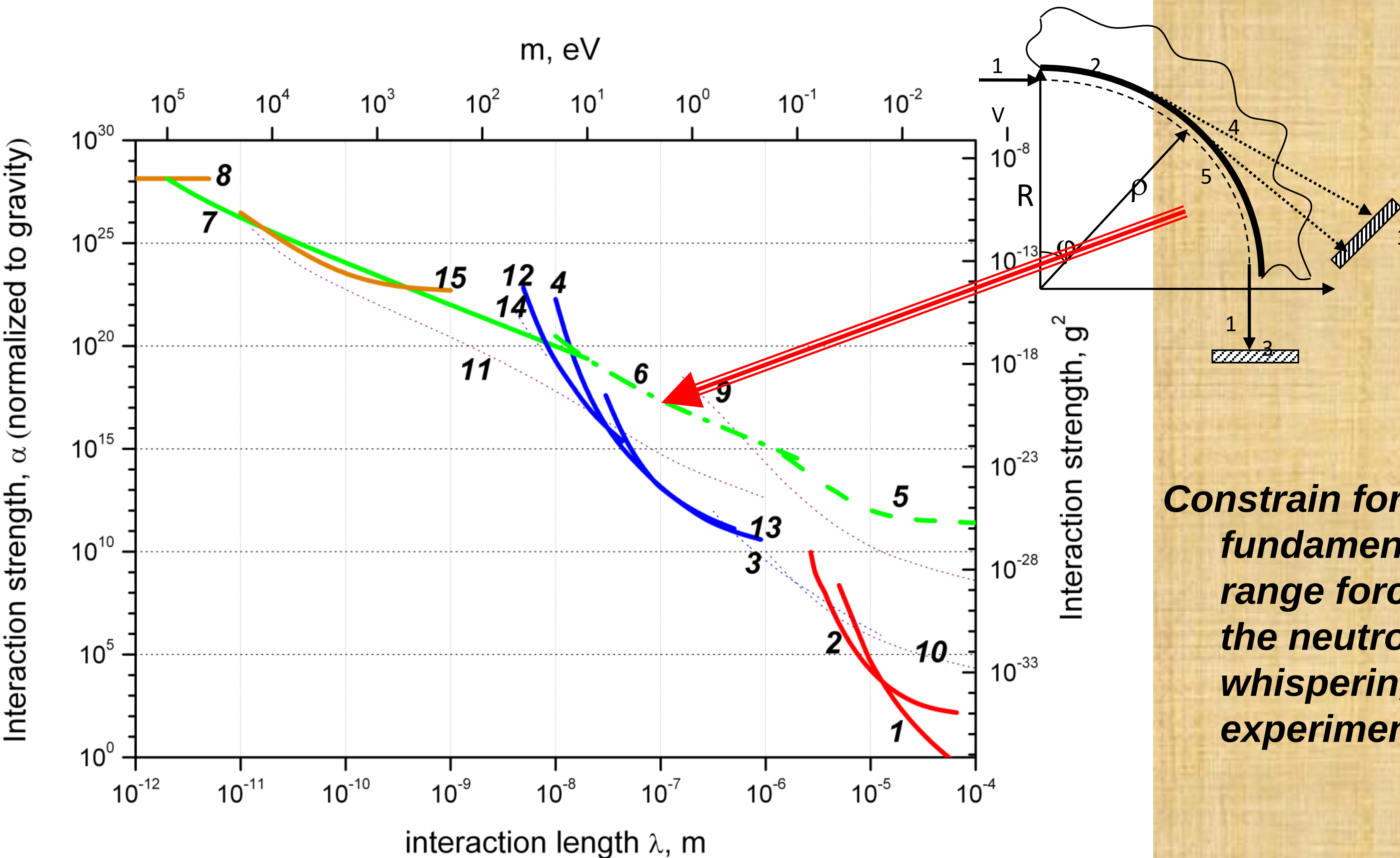


Neutrons entering from the mirror edge

Experiment

Neutrons populate quantum states states through the entrance edge of a truccated cylinder and are counted behind the exit edge

Results: NEUTRON RAINBOW



Constrain for fundamental short-range forces from the neutron whispering gallery experiment

Conclusion (on centrifugal quantum states)

1. First observation of quasi-stationary quantum states of cold neutrons in vicinity of a 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 for constraining fundamental short-range forces
4. Such an experiment is feasible with anti-hydrogen
5. The GRANIT spectrometer could be used for one-to-one prototyping of an experiment measuring quantum states of anti-hydrogen atoms

Conclusion

1. Observation of gravitational and centrifugal quantum states of slow neutrons
2. The first direct demonstration of the Weak equivalence principle for an object in a quantum state.
3. Long lifetimes of neutrons in these quantum states allow one using them for precision studies
4. Very similar precision experiments could be performed with anti-matter atoms