НИЯУ МИФИ

Seminar

Gravitational behavior of antihydrogen at rest

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P.N.Lebedev Physical Institute of the Russian Academy of Sciences

GBAR

GRASIAN

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Plan of the talk

- Проект GBAR: мотивация, замысел, статус
- Гравитационные квантовые состояния антиводорода
- Заключение

GBAR

Irfu

RIKEN

Laboratoire Kastler Brossel
Physique quantique et applications

東京大学
THE UNIVERSITY OF TOKYO

Swansea University
School of Physical Sciences

IPCMS

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MOTIVATION

A direct test of the Equivalence Principle with antimatter

The acceleration imparted to a body by a gravitational field is independent of the nature of the body :

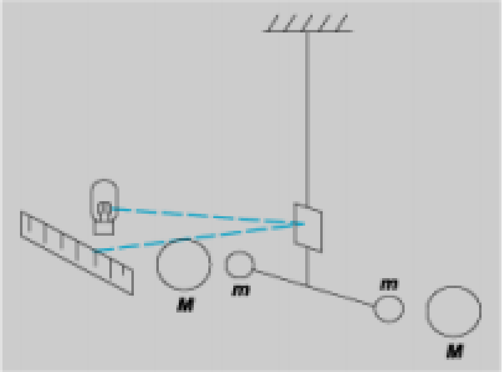
Inertial mass = gravitational mass

Tested to a very high precision with many materials

Weak Equivalence Principle (torsion pendulum)

$$(\Delta a / a)_{Be/Ti} = (0.3 \pm 1.8) \times 10^{-13}$$

S.Schlamminger et al, Phys Rev Lett 100 (2008) 041101



Strong Equivalence Principle (Lunar Laser Ranging)

$$(\Delta a / a)_{Earth/Moon} = (-1.0 \pm 1.4) \times 10^{-13}$$

J.G.Williams et al, Phys Rev Lett 93 (2004) 261101

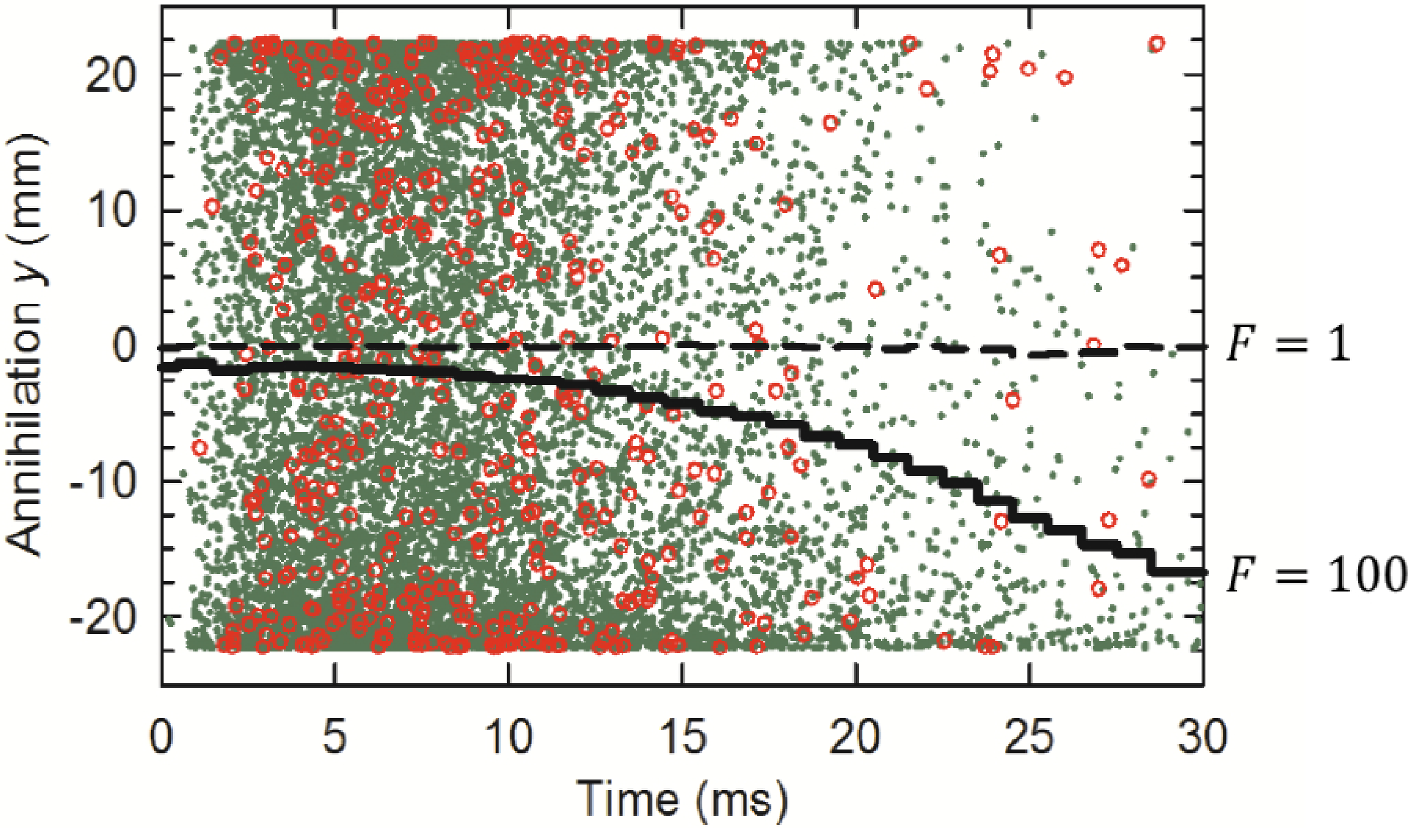
CPT symmetry assumed

(see talk by E. Adelberger at gbar2011 workshop http://indico.in2p3.fr//event/gbar2011.fr)

Antimatter Experiments: one result

Antihydrogen

$$F = M_G / M$$



Green dots---simulated annihilations

Red circles---434 Observed annihilations

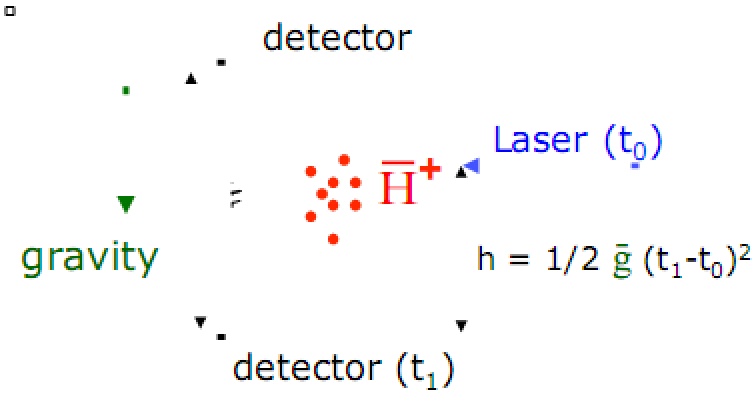
Vertical position of annihilation vertex during release of trapping field

KEY IDEA

Using $\bar{H}^+$ to get $\bar{H}$ atoms

- Produce ion $\bar{H}^+$
- Sympathetic cooling 10 μK
- Photodetachment of e^+
- Time of flight

Error dominated by temperature of $\bar{H}^+$



J.Walz & T. Hänsch, General Relativity and Gravitation, **36** (2004) 561.

Relative Precision on $\bar{g}$:

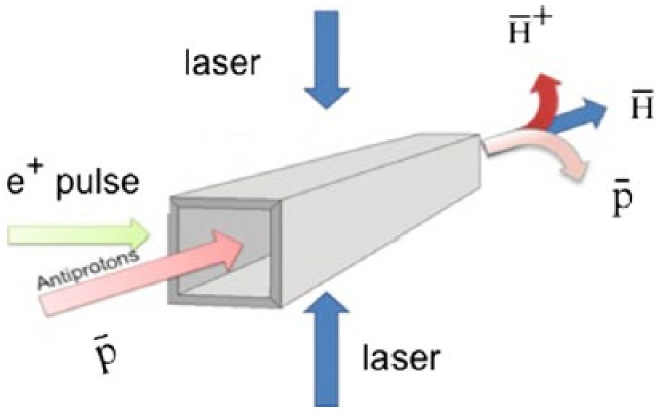
$\bar{H}$ detected free falls	$\Delta g/g$
$1.5\ 10^5$	0.001
1500	0.01

$h = 20$ cm → $\Delta t = 202$ ms

$h = 15$ cm → $\Delta t = 175$ ms

First stage

$\bar{H}^+$ Production

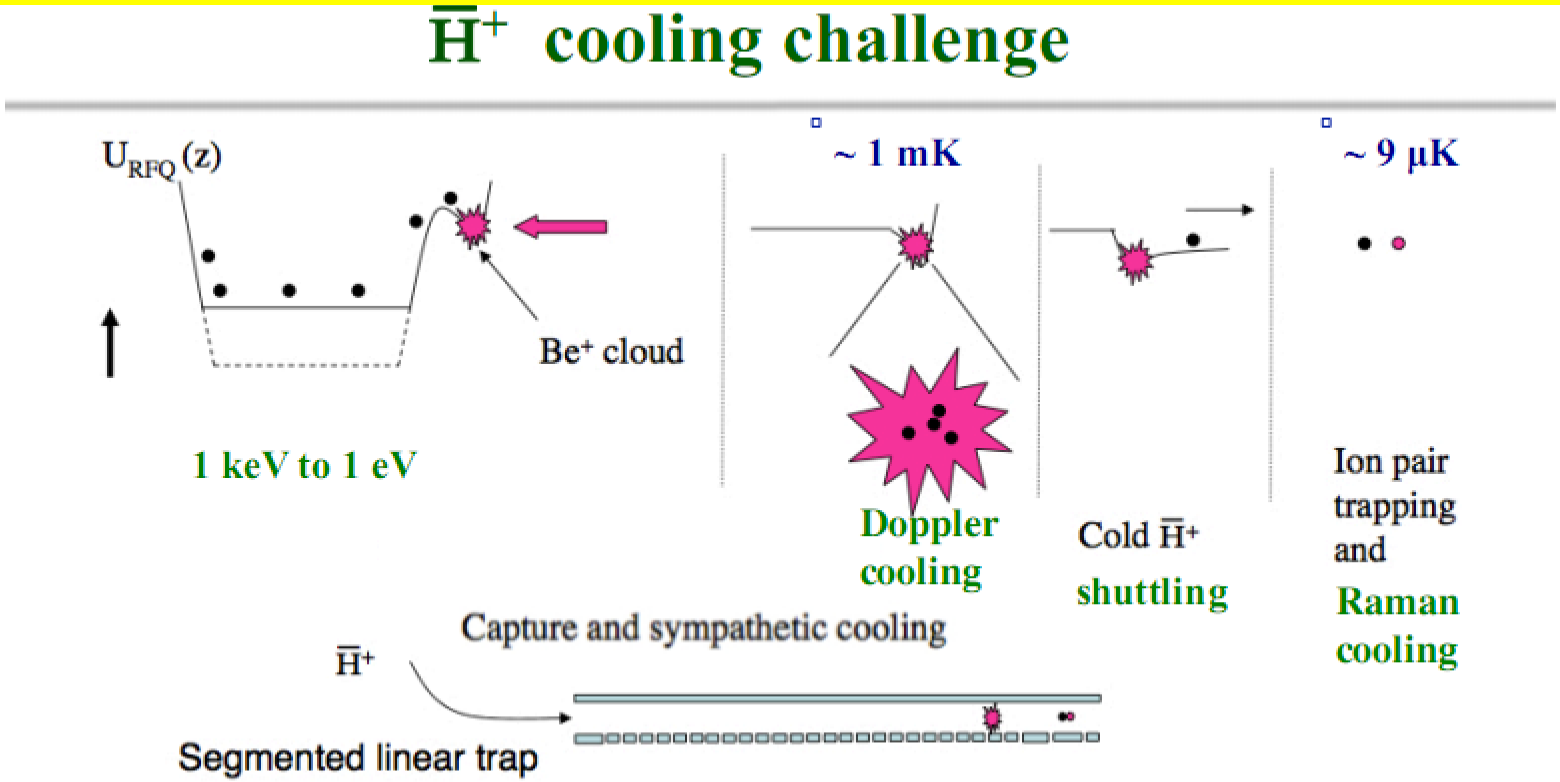


$$\bar{p} + Ps \rightarrow \bar{H} + e^-$$

$$\bar{H} + Ps \rightarrow \bar{H}^+ + e^-$$

Ortho-positronium

Ion cooling

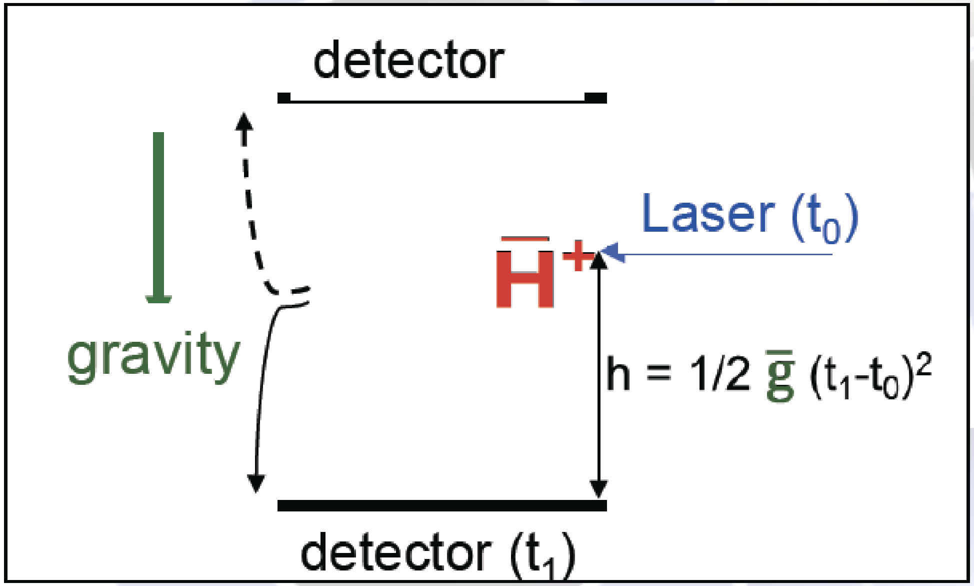


NIST group
M. D. Barrett, ..., D. Wineland, PRA ***68****, 042302 (2003)*
Sympathetic cooling of $^9Be^+$ and $^{24}Mg^+$ for quantum logic

Gbar

Falling antihydrogen

principle



J.Walz & T. Hänsch
General Relativity and Gravitation, 36 (2004) 561

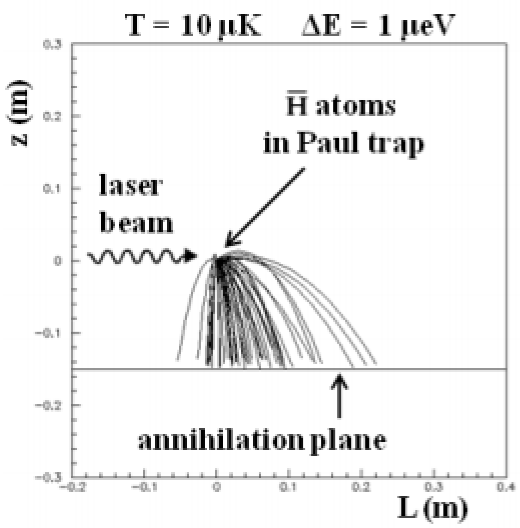
$$z = z_0 + v_{z0}t + \frac{1}{2}\overline{g}t^2$$

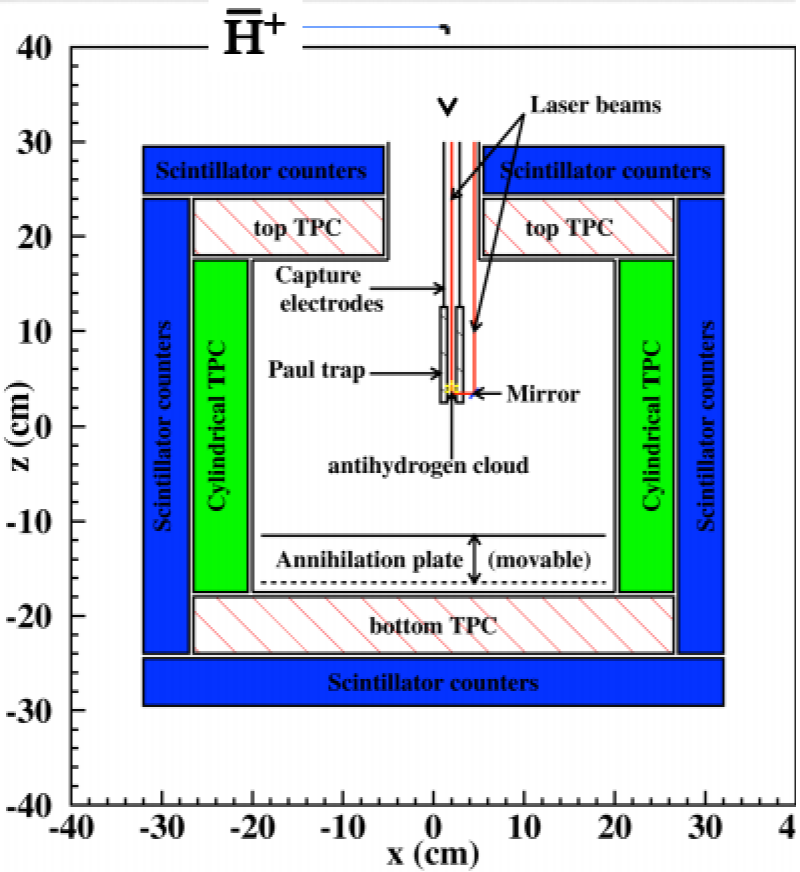
Velocity fluctuation	100 m/s	3 m/s	0.1 m/s
Temperature equivalent	1 K	1 mK	1 μK

Desired range

FREE FALL

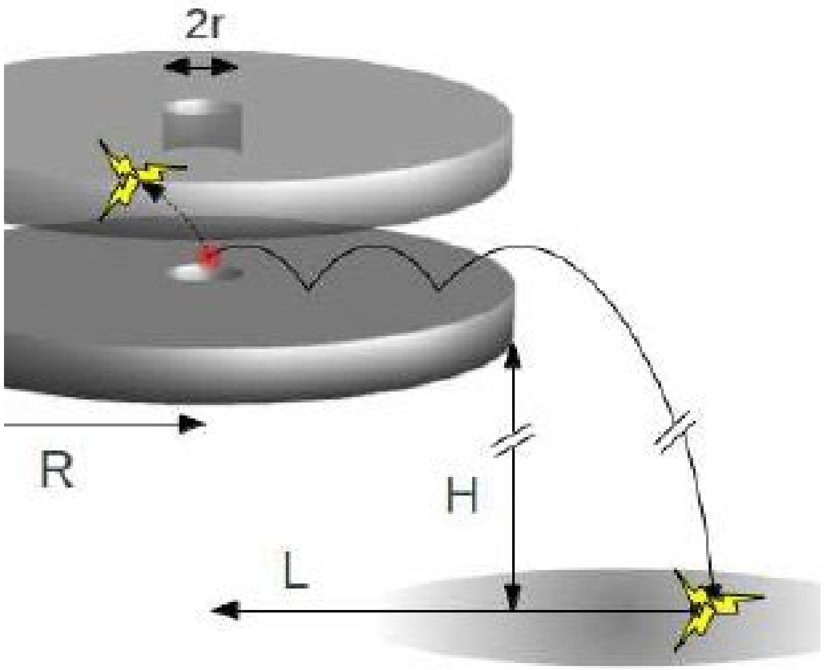
$\bar{H}$ free fall detection





Detection	Requirement
TOF precision	150 μs
Annihil. vertex precision	2 mm
Background rejection	event topology

Antihydrogen bouncing on the table



PHYSICAL REVIEW A **83**, 032903 (2011)

Gravitational quantum states of Antihydrogen

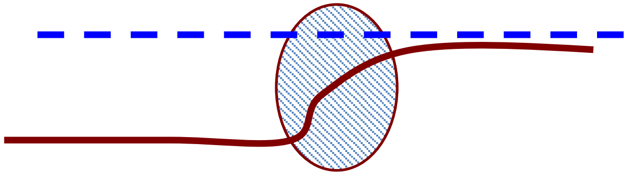
A. Yu. Voronin, P. Froelich, and V. V. Nesvizhevsky

Quantum reflection

- Over-barrier Reflection from the fast changing attractive potential

$$\frac{d\lambda_B(z)}{dz} \geq 1; \;\; \lambda_B(z) = \frac{2\pi\hbar}{\sqrt{2M(E-V(z))}}$$

$$z \geq \sqrt{2MC_4}$$



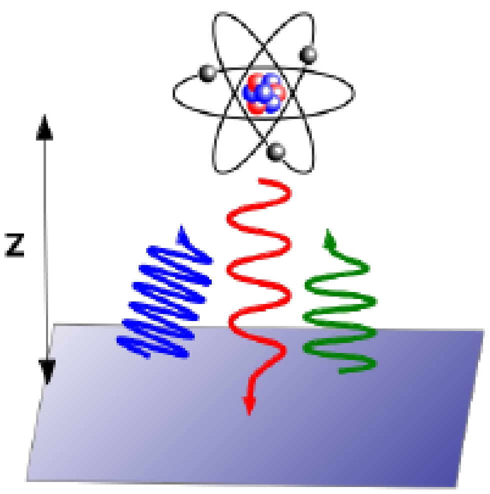
$$\Psi(z \to -\infty) = Te^{-ikz}$$

$$\Psi(z \to +\infty) = e^{-ikz} - Se^{ikz} \;\; ; S = 1 - 2ika \;\; ; a = \mathrm{Re}\, a - i\left|\mathrm{Im}\, a\right|$$

$$R = \left|S\right|^2 = 1 - 4k\left|\mathrm{Im}\, a\right| \to 1; P = 4k\left|\mathrm{Im}\, a\right| \to 0$$

The Casimir-Polder force

Electromagnetic (EM) modes are modified when the atom comes close to the detector:
⇒ the EM ground state (vacuum) energy changes
⇒ attractive Casimir-Polder force between atom and detector

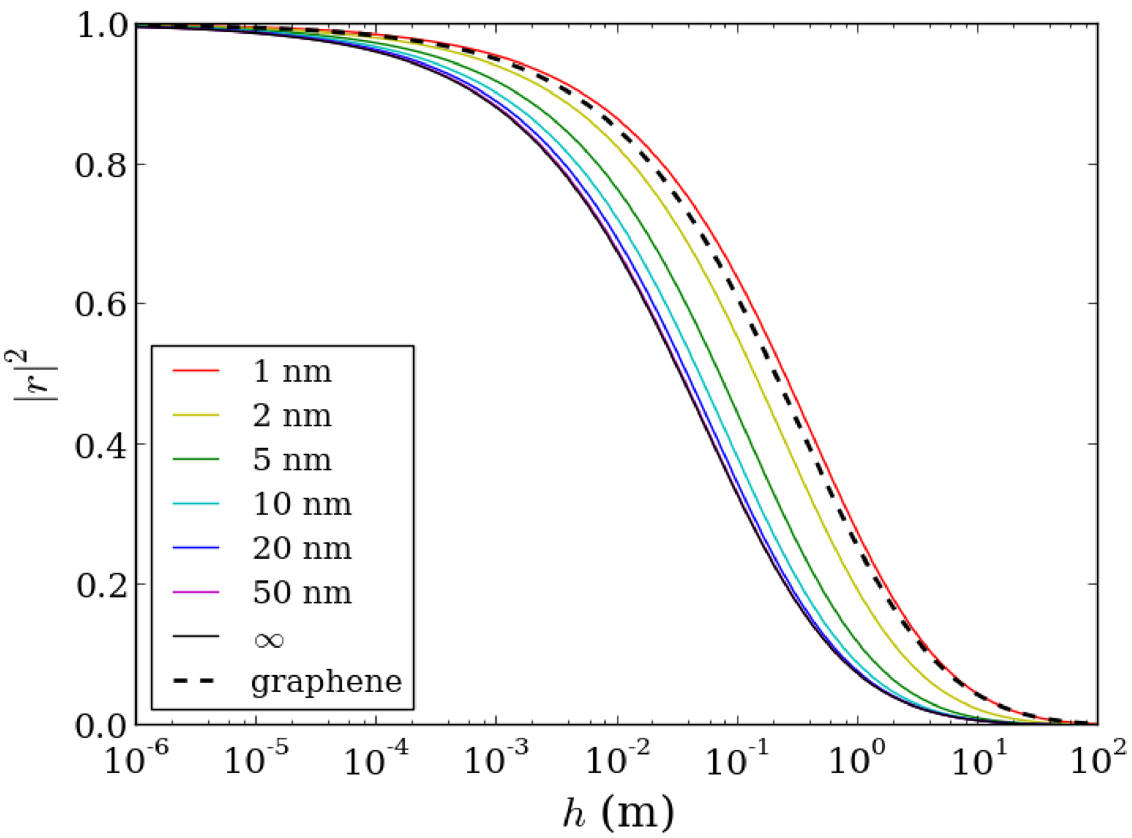


Casimir 1948 : long-range interaction energy between an atom and a perfectly conducting mirror:

$$V^*(z) = -\frac{3\hbar c}{8\pi z^4}\frac{\alpha(0)}{4\pi\epsilon_0} = -\frac{C_4^{perfect}}{z^4}$$

For H and $\overline{\mathrm{H}}$, $C_4^{perfect} \approx 73.6\ E_h a_0^4$
$V(35\text{ nm}) \approx$ - $mg \times 10$ cm

Reflection coefficient



PHYSICAL REVIEW A **87**, 022506 (2013)

Quantum reflection of antihydrogen from nanoporous media

G. Dufour,[1] R. Guérout,[1] A. Lambrecht,[1] V. V. Nesvizhevsky,[2] S. Reynaud,[1] and A. Yu. Voronin[3]

Quantum reflection of antihydrogen from a liquid helium film

P.-P. Crépin[1] et al

Europhysics Letters, Volume 119, Number 3

Gravitational quantum states?

$$\varepsilon_g = \sqrt[3]{\frac{\hbar^2 M g^2}{2}} = 0.61\ 10^{-12}\text{eV};$$

$$l_g = \sqrt[3]{\frac{\hbar^2}{2M^2 g}} = 5.87\ 10^{-6} m.$$

$$\left[-\frac{d^2}{dx^2} + x - \lambda\right] \mathrm{F}(x) = 0,\ F(0) = 0$$

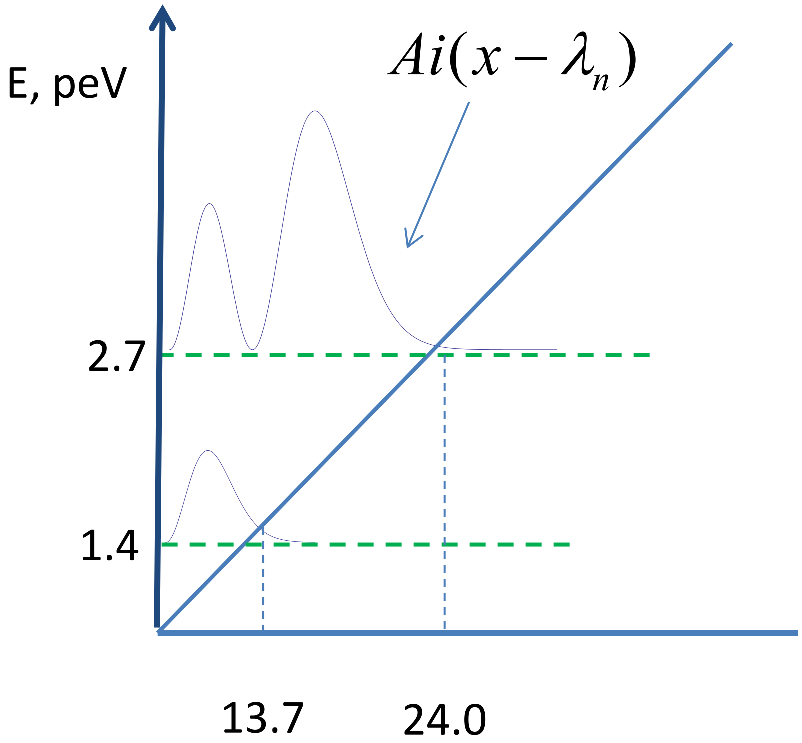
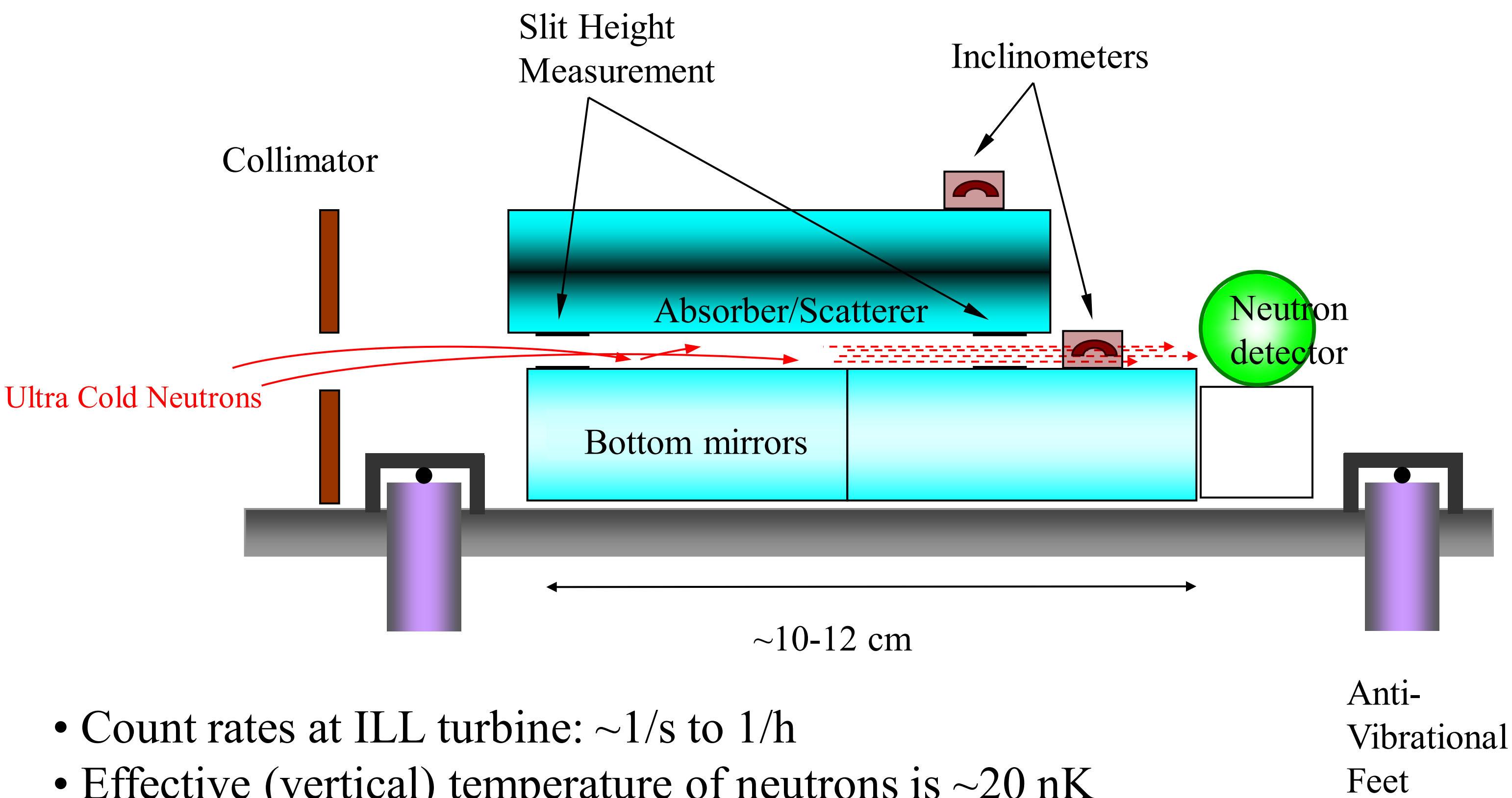


TABLE I. The eigenvalues, gravitational energies, and classical turning points of a quantum bouncer with the mass of (anti)hydrogen in the Earth's gravitational field.

n	λ_n^0	E_n^0 (peV)	z_n^0 (μm)
1	2.338	1.407	13.726
2	4.088	2.461	24.001
3	5.521	3.324	32.414
4	6.787	4.086	39.846
5	7.944	4.782	46.639
6	9.023	5.431	52.974
7	10.040	6.044	58.945

First Observation: Gravitational States of Neutrons
Nesvizhevsky et al. Nature 415, 297 (2002)



- Count rates at ILL turbine: ~1/s to 1/h
- Effective (vertical) temperature of neutrons is ~20 nK
- Background suppression is a factor of $\sim 10^8$-10^9
- Parallelism of the bottom mirror and the absorber/scatterer is $\sim 10^{-6}$

Spectroscopy- to induce transitions between gravitational states

$$\varepsilon_g = \sqrt[3]{\frac{\hbar^2 M g^2}{2}} = 0.61\ 10^{-12} \mathrm{eV};$$

$$l_g = \sqrt[3]{\frac{\hbar^2}{2M^2 g}} = 5.87\ 10^{-6} m.$$

PHYSICAL REVIEW LETTERS **126,** 170403 (2021)

Impulsively Excited Gravitational Quantum States: Echoes and Time-Resolved Spectroscopy

I. Tutunnikov,[1] K. V. Rajitha,[1] A. Yu. Voronin,[2,*] V. V. Nesvizhevsky,[3,†] and I. Sh. Averbukh[1,‡]

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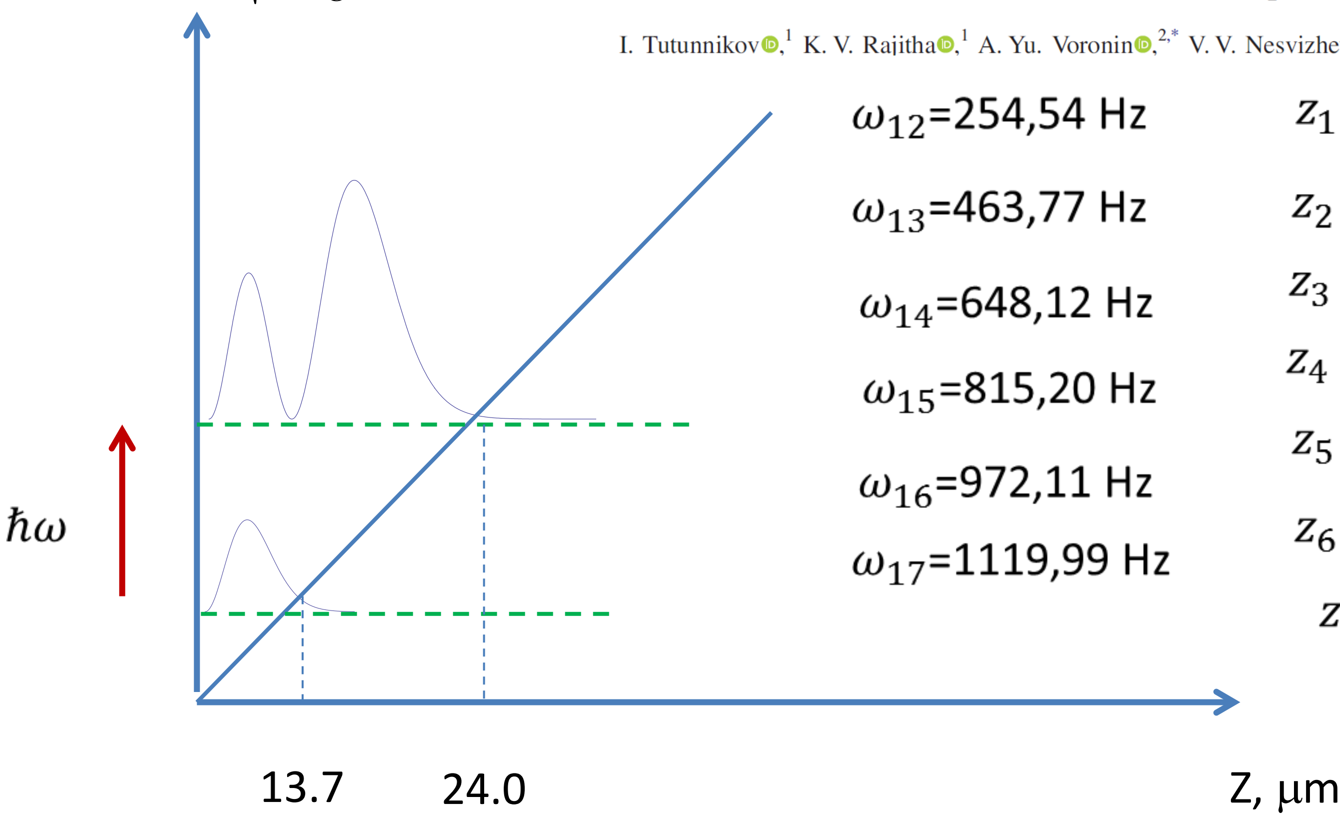


ω_{12}=254,54 Hz

ω_{13}=463,77 Hz

ω_{14}=648,12 Hz

ω_{15}=815,20 Hz

ω_{16}=972,11 Hz

ω_{17}=1119,99 Hz

$z_1 = 13.7\ \mu m$

$z_2 = 24.0\ \mu m$

$z_3 = 32.4 \mu m$

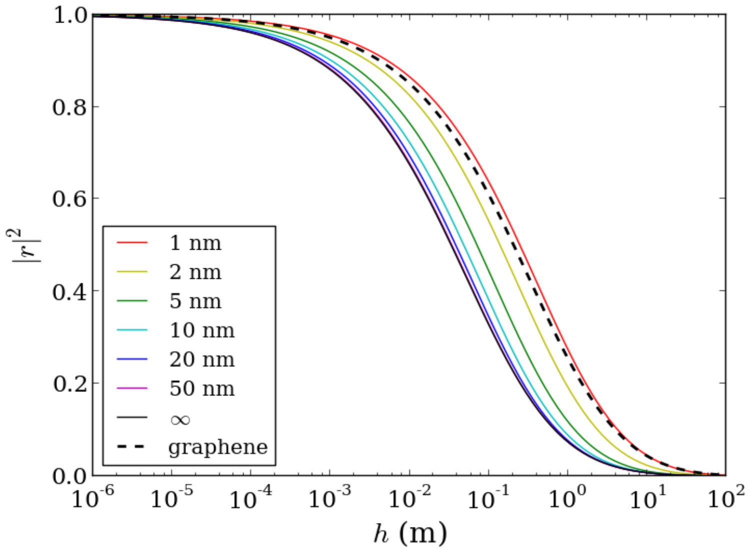
$z_4 = 39.8\ \mu m$

$z_5 = 46.6\ \mu m$

$z_6 = 52.9\ \mu m$

$z_7 = 58.9\ \mu m$

Antihydrogen GQS due to Quantum reflection



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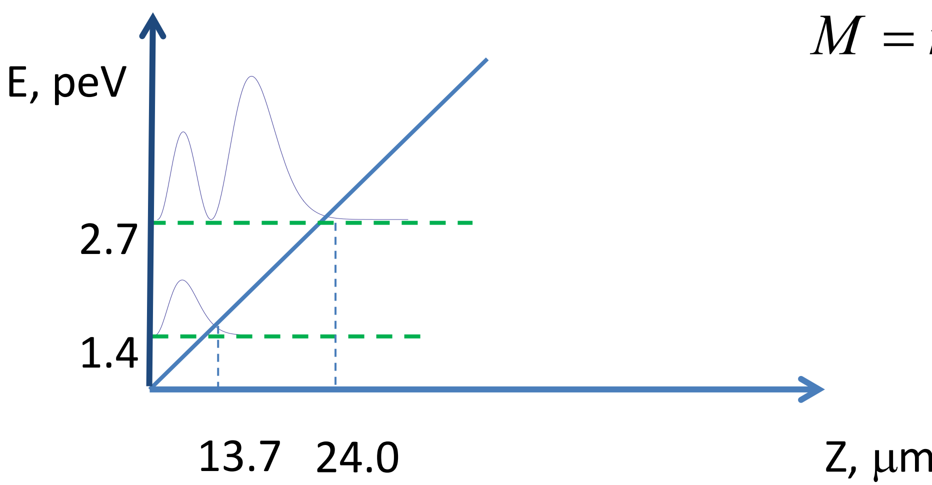
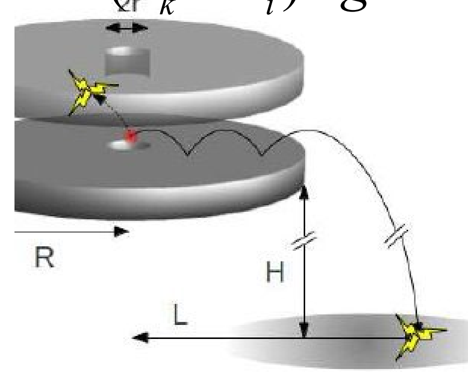
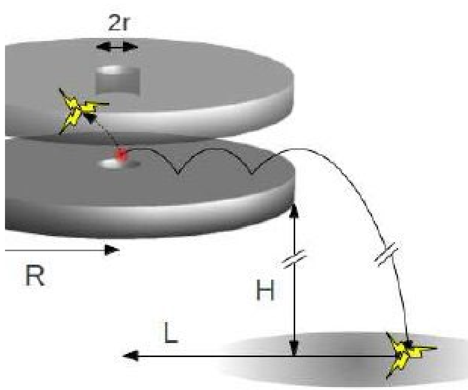
GBAR quantum fall

$$M = m \Rightarrow M = \frac{2\omega_{ik}^3}{(\lambda_k - \lambda_i)^3} \frac{\hbar}{g^2}$$





Interference of gravitational states



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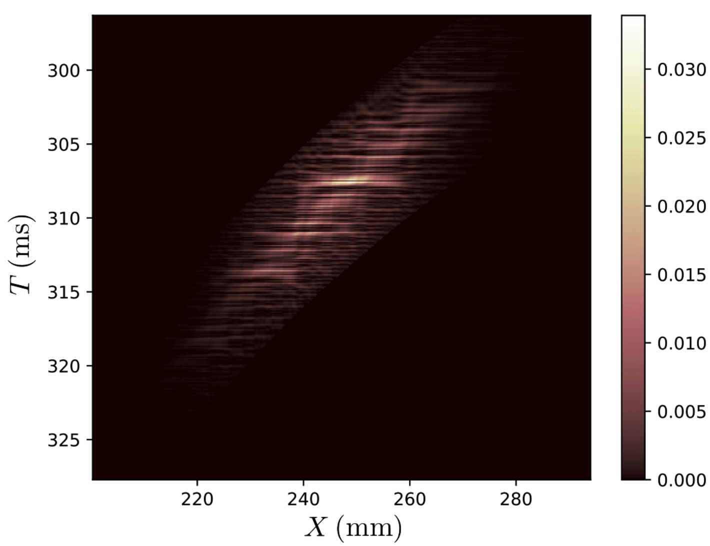

GBAR quantum fall

Quantum interference test of the equivalence principle on antihydrogen

P.-P. Crépin, C. Christen, R. Guérout, V. V. Nesvizhevsky, A.Yu. Voronin, and S. Reynaud

Phys. Rev. A **99**, 042119

Gravitational states and Gravitational mass

Classical: $\not{m}\ddot{z} = \not{M}g \rightarrow \ddot{z} = g \rightarrow T = \sqrt{2H/g}$

Quantum: $\left[-\frac{\hbar^2}{2m}\frac{d^2}{dz^2} + Mgz - E\right]\Psi(z) = 0 \Rightarrow \left[-\frac{d^2}{dx^2} + x - \lambda_n\right]\mathrm{F}(x) = 0$

$$\varepsilon_g = \sqrt[3]{\frac{\hbar^2 M^2 g^2}{2m}} = 0.61\ 10^{-12}\,\mathrm{eV};\quad l_g = \sqrt[3]{\frac{\hbar^2}{2Mmg}} = 5.87\ 10^{-6}\,m$$

$$m = \frac{\hbar^2}{2\varepsilon_g l_g^2};\quad M = \frac{\varepsilon_g}{g l_g}$$

$$M = m \Rightarrow \frac{\hbar}{\varepsilon_g} = \sqrt{\frac{2l_g}{g}} \text{ or } \mathrm{T} = \sqrt{\frac{2H}{g}}$$

EP test by measuring time and spatial scales of GQS

Conclusions

- GBAR project- crossroad of multiple intriguing physical problems
- Gravitational quantum states of Antihydrogen: simplest bound quantum system, determined by gravity. Perfect laboratory for EP, non-newtonian gravity, provide accuracy 3000 better than classical approach with same parameters
- Interested contributors are welcome!