

EXA 2014, WIEN

Resonance spectroscopy of Gravitational Quantum States of **Antihydrogen**

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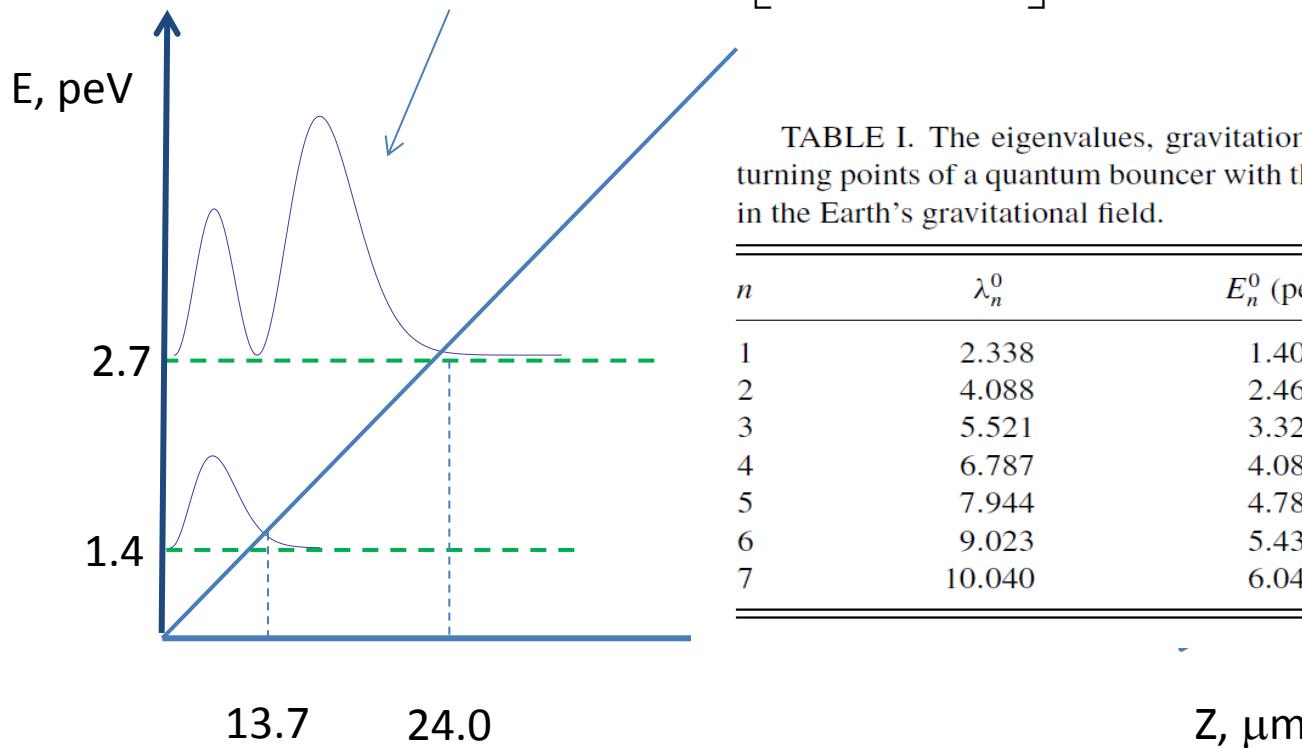
NEUTRONS
FOR SCIENCE®

Plan of the talk

- Gravitational states of antihydrogen? Yes, it is possible!
- Resonance spectroscopy of GraviAtom
- Gravitational mass out of resonance spectroscopy

Gravitational quantum states?

State of motion of a quantum particle, which is localized near reflecting surface in a gravitational field of the Earth.



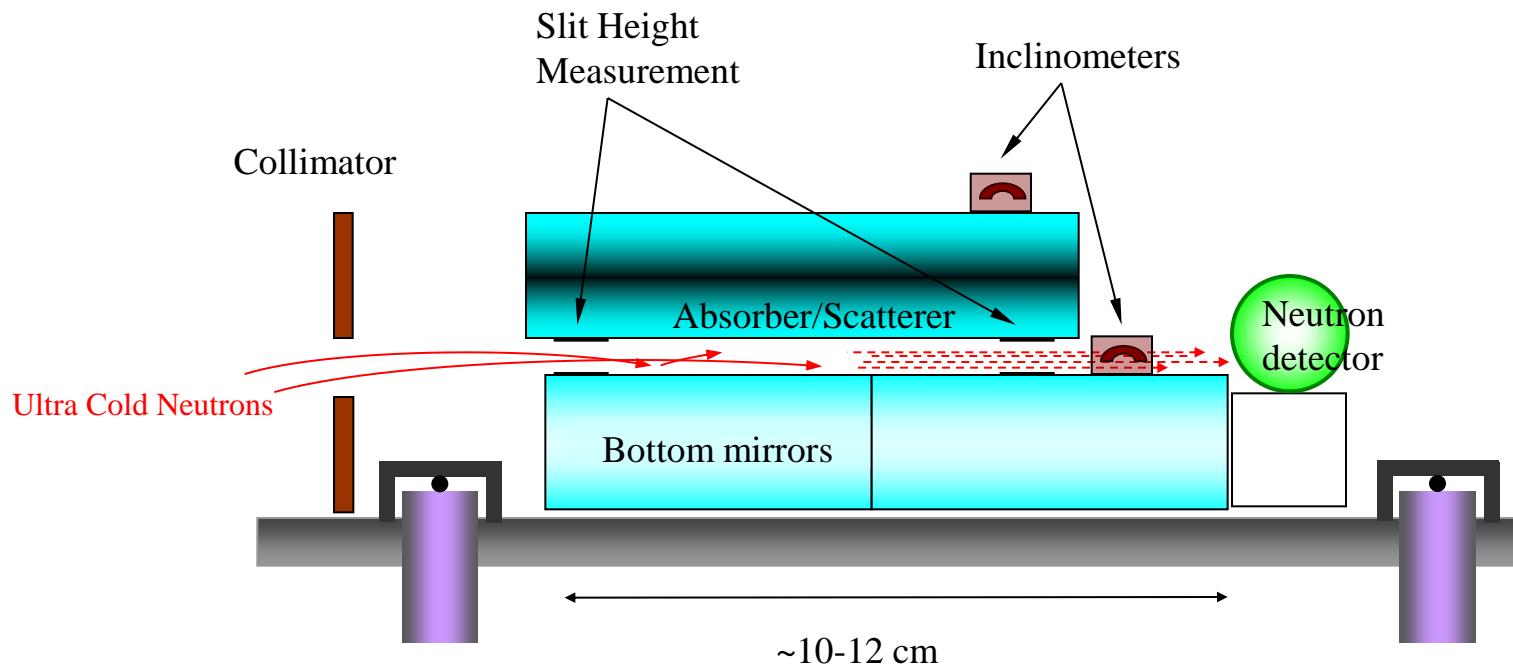
$$\left[-\frac{d^2}{dx^2} + x - \lambda \right] F(x) = 0, \quad F(0) = 0$$

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 ~ 10^8 - 10^9
- Parallelism of the bottom mirror and the absorber/scatterer is ~ 10^{-6}

Anti-
Vibrational
Feet



GRANIT SPECTROMETER

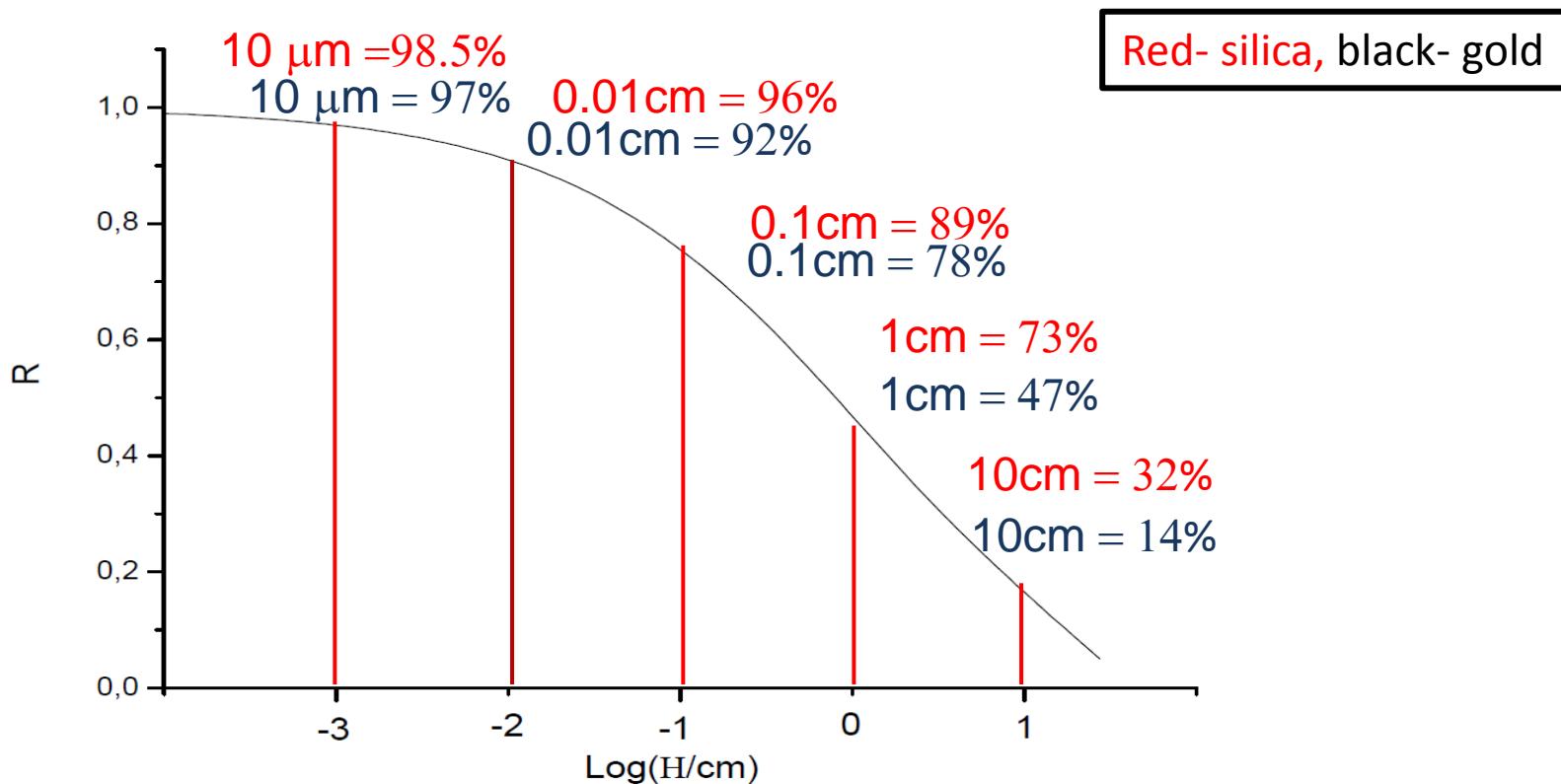
Gravitational states of Antihydrogen: Seems Impossible? Quantum Reflection!

$$R \approx 1 - 2 |\text{Im}(a)| / \lambda; |\text{Im}(a)| \approx 29 \text{ nm}; \lambda \approx 6 \mu\text{m}$$

$$R \rightarrow 1 \text{ when } \lambda \rightarrow \infty$$

Steep attractive potential reflects slow atoms!

Gravitational states of Antihydrogen: Seems Impossible? Quantum Reflection!

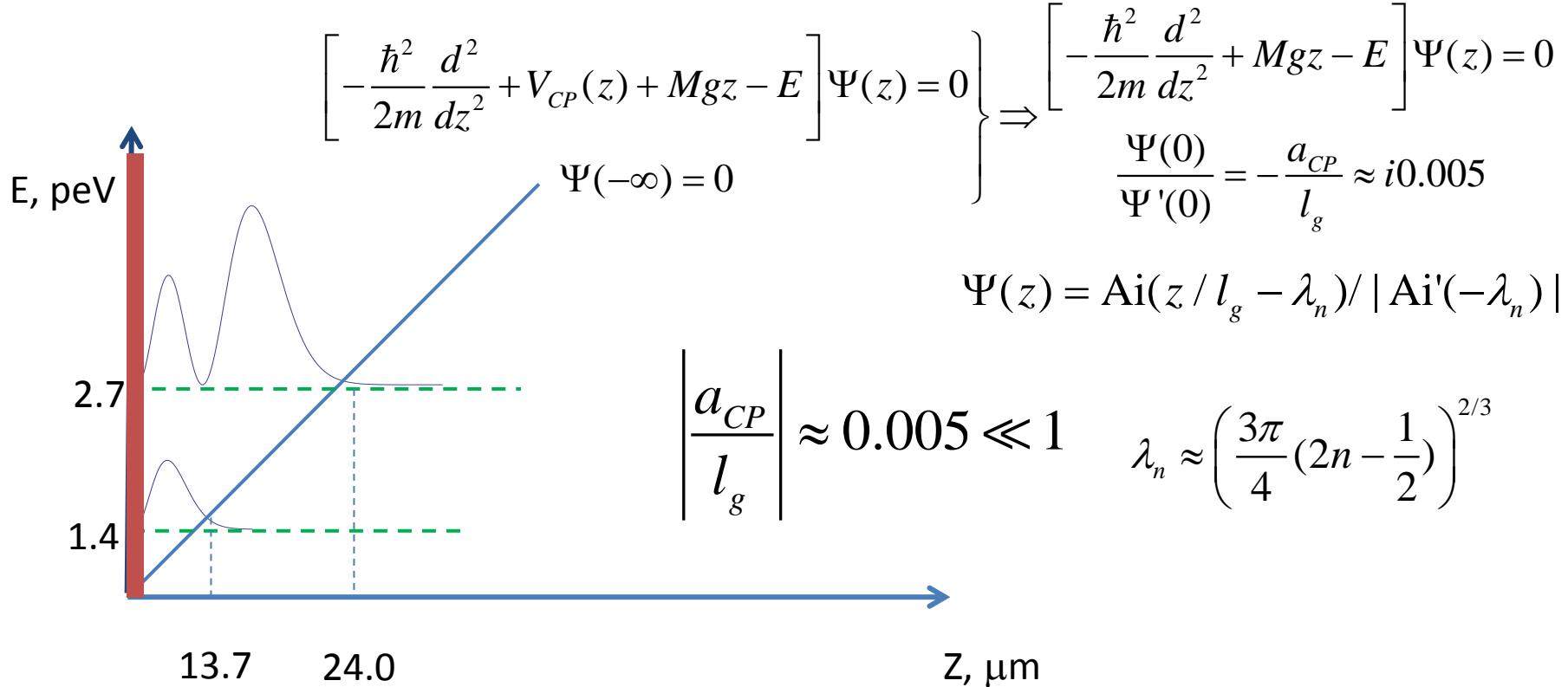


A. Yu. Voronin, P. Froelich, and B. Zygelman, Phys. Rev. A **72**, 062903 (2005).

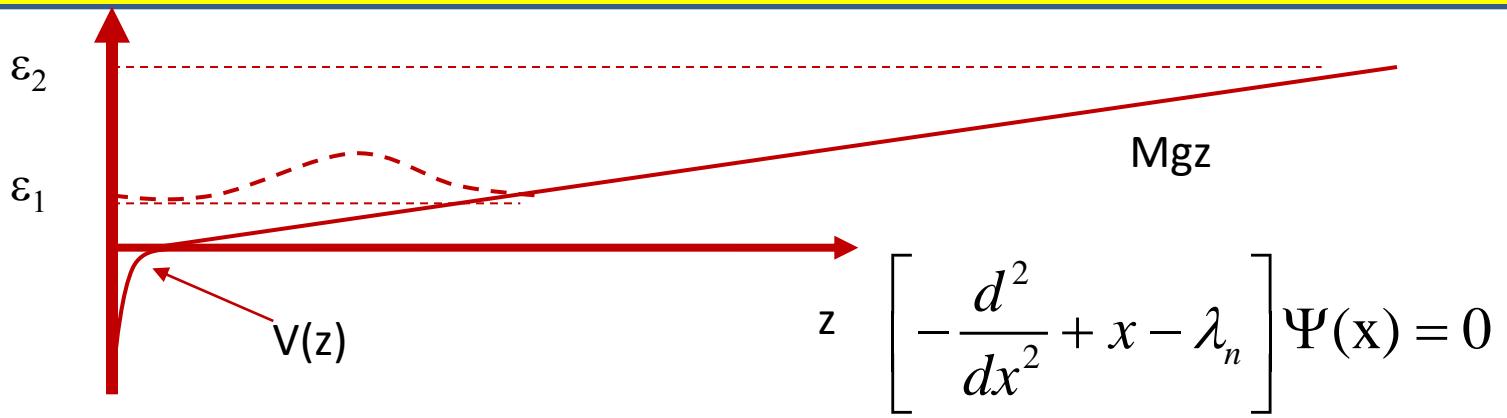
G. Dufour, A. Gérardin, R. Guérout, A. Lambrecht, V. V. Nesvizhevsky, S. Reynaud, A. Yu. Voronin Phys. Rev. A 87, 012901 (2013)

Gravitational states of antihydrogen

Quantum reflection is about 97% - it works like a reflecting wall



Correction by Casimir-Polder potential + annihilation



$$|a|/l_0 \approx 0.005$$

$$\frac{\Psi(0)}{\Psi'(0)} = -\frac{a_{CP}}{l_g} \approx i0.005$$

Correction by Casimir-Polder and annihilation:

$$\tilde{\lambda}_n = \lambda_n + a / l_g$$

$$\epsilon_n = \epsilon_0 (\lambda_n + \operatorname{Re} a / l_g) \quad \Gamma = 2\epsilon_0 |\operatorname{Im} a| / l_g$$

$$\tau = \frac{l_g}{\epsilon_g} \frac{\hbar}{2|\operatorname{Im} a|} = \frac{\hbar}{2Mg|\operatorname{Im} a|} \approx 0.1s$$

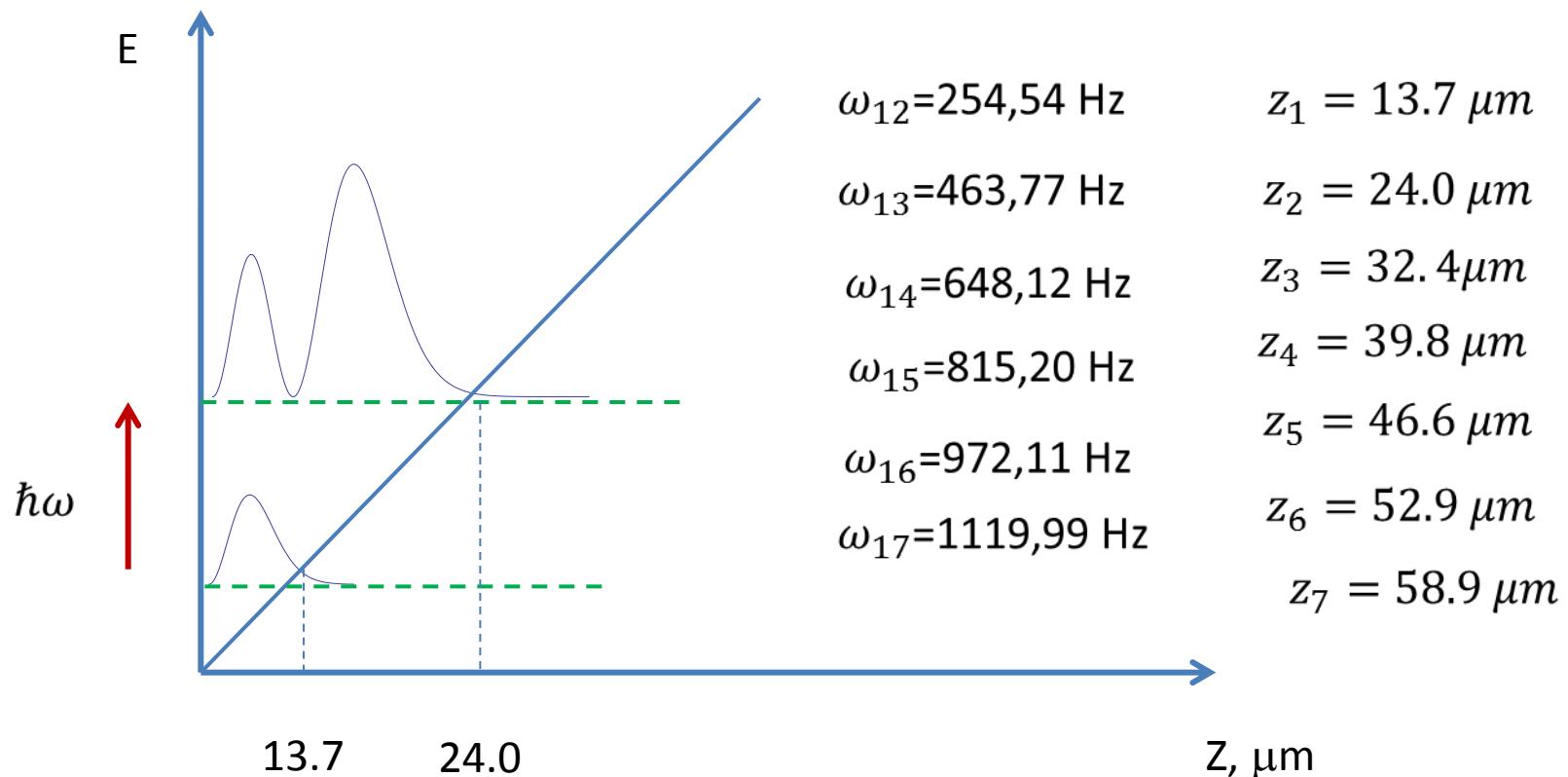
All states have equal shift and lifetime $\sim 0.1s \Rightarrow$
 No surface effects in transition frequencies

Effects of surface

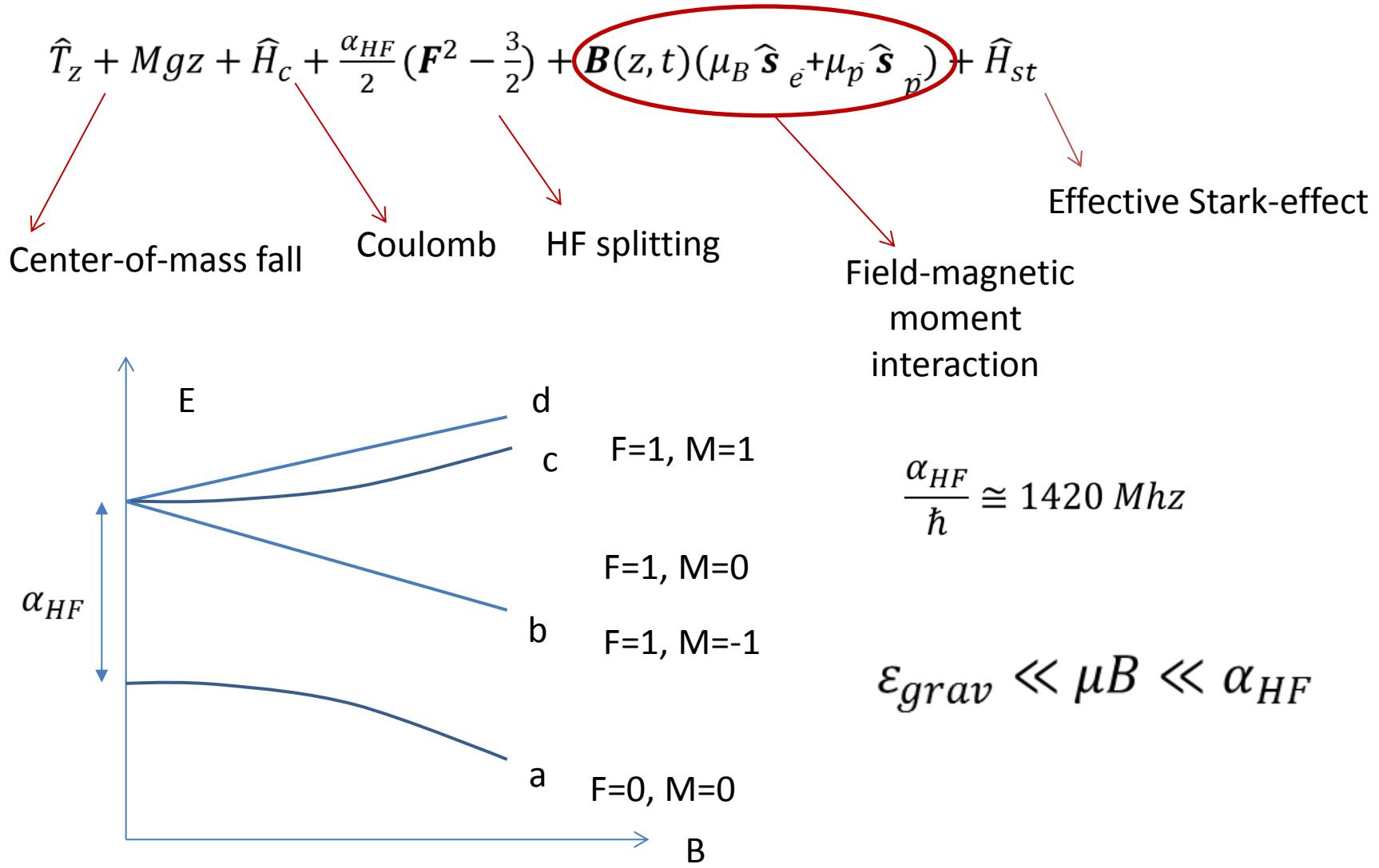
- Hierarchy of scales $l_g \gg |a_{CP}|$: gravity and surface-atom interaction are factorized
- Annihilation in the bulk of the wall: short – range atom-wall interactions are washed out
- Small annihilation width of gravitational states: compromise between long life-time and observation
- The same shift of all energy levels states – cancels out in transition frequency

Spectroscopy- to induce transitions between gravitational states with alternating magnetic field

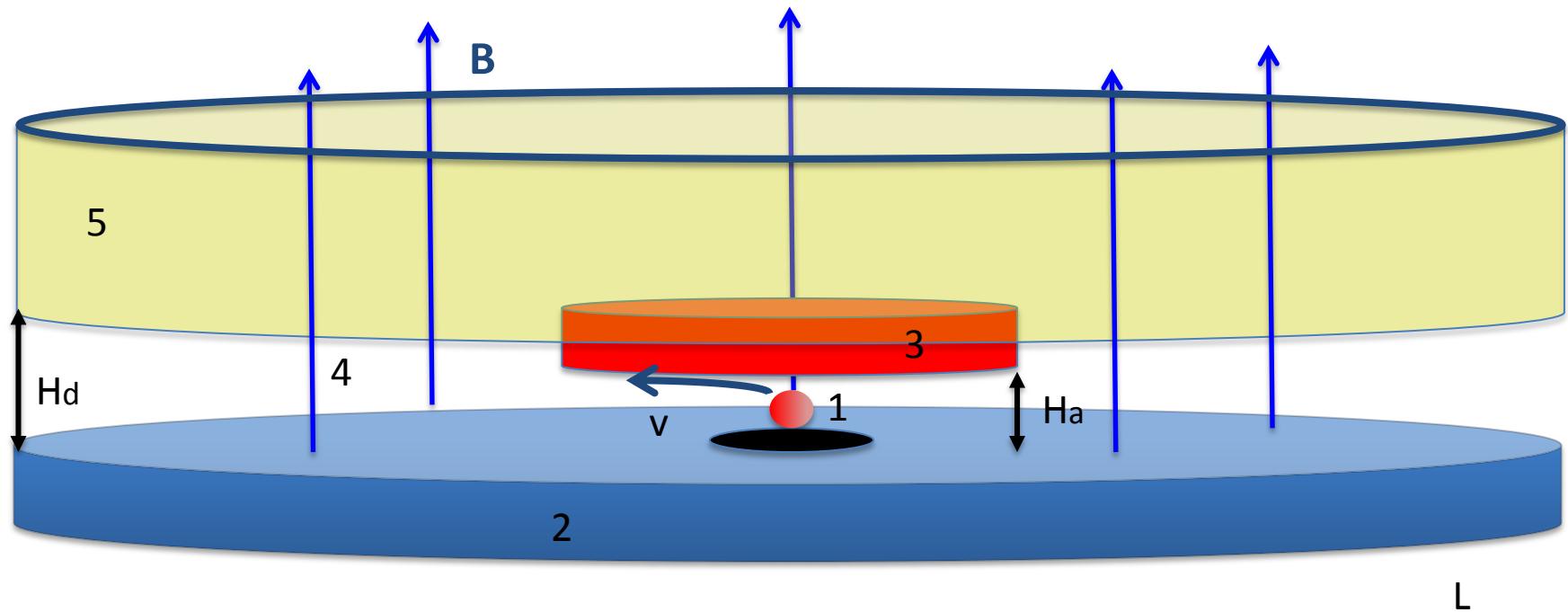
Developed for neutrons by V. Nesvizhevsky, S. Baessler, G. Pignol, K. Protassov, A.Voronin



Antihydrogen in Magnetic Field



Possible scheme of flow-throw experiment



1-source of ultracold antihydrogen, 2-mirror, 3- absorber, 4- magnetic field,
5- detector

$$v \approx 1m/s, H_a = 15\mu m, H_d = 25\mu m, B_0 \approx 10Gs, \beta \approx 10Gs/m, L = 30cm$$

“Graviatom”- Beautiful benchmark system

$$\begin{cases} i\hbar \frac{d}{dt} \Psi(z, t) = \left(-\frac{\hbar^2}{2m} \frac{d^2}{dz^2} + Mgz + V_0 z \cos(\omega t) \right) \Psi(z, t) \\ \frac{\Psi(0)}{\Psi'(0)} = -\frac{a_{CP}}{l_0} \end{cases}$$

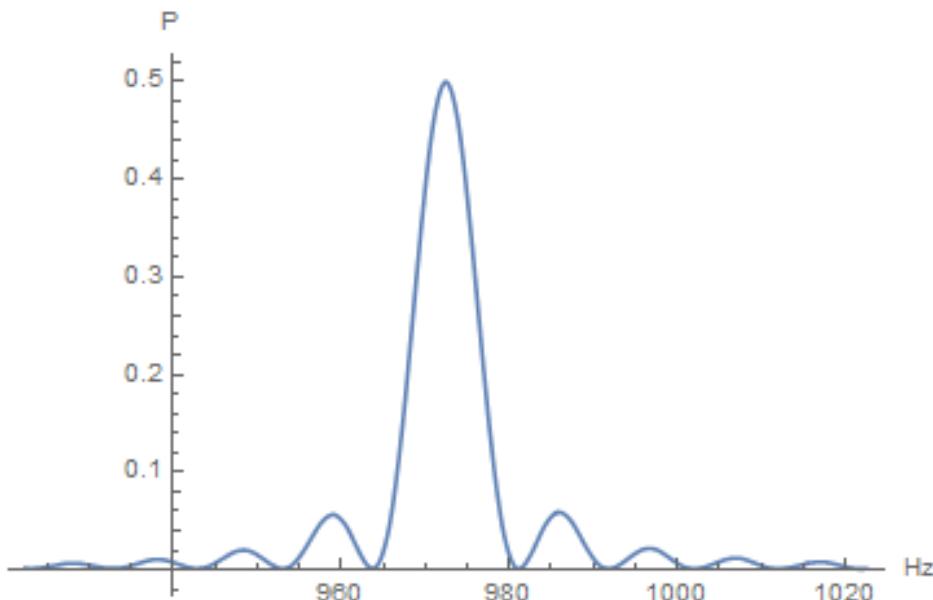
Beyond Rabbi formula. Second order resonance shift:

$$\delta = \frac{V_0^2}{4} \left(\sum_{k=1} \frac{|\langle f | z | k \rangle|^2}{2E_f - E_i - E_k} + \sum_{k \neq i} \frac{|\langle f | z | k \rangle|^2}{E_i - E_k} - \sum_{k=1} \frac{|\langle i | z | k \rangle|^2}{2E_i - E_f - E_k} - \sum_{k \neq n_1} \frac{|\langle i | z | k \rangle|^2}{E_f - E_k} \right)$$
$$\langle k | z | n \rangle = l_0 (-1)^{k+n+1} \frac{2}{(\lambda_k - \lambda_n)^2}$$

Minimum shift for transitions 1->3, 1->6, 1->9

Transition probability

$$P_{ik} = \frac{1}{2} \frac{\Omega_{ik}^2}{\Omega_{ik}^2 + \hbar^2 \Delta^2} \sin^2\left(\frac{t}{\hbar} \sqrt{\Omega_{ik}^2 + \hbar^2 \Delta^2}\right) \exp(-\Gamma t)$$
$$\Omega_{ik} = \frac{(\mu_B + \mu_{\bar{p}}) \beta l_g^3}{\hbar(z_k - z_i)^2}$$



Transition probability as a function of frequency. Transition 1->6

$f_{res} = 972.459$ Hz $\Delta = -0.02$ Hz Time of observation $t=0.1$ s

EP and gravitational mass

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

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

PRECISION

$$\varepsilon \approx \frac{3\gamma}{2\sqrt{N_{\bar{H}}}\omega}; N_{\bar{H}} = 10^2$$

$$\varepsilon_{1-5} \approx 10^{-3}$$

Gravitational states and Gravitational mass

Classical: $m\ddot{z} = Mg \rightarrow \ddot{z} = g \rightarrow T = \sqrt{2H / g}$

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

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

$$E_n = \varepsilon_g \lambda_n$$

$$z = l_g x \quad \Psi_n(z) = \frac{1}{\sqrt{l_g}} F(z / l_g - E_n / \varepsilon_g)$$

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

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

Gravitational states are all about energy and spatial scales

Conclusions

- Gravitational states of Antihydrogen: simplest bound antimatter quantum system, determined by gravity. Effects of surface are canceled out.
- Gravitational states of Antihydrogen- metastable and long-living, easy to study due to annihilation signal
- Gravitational states- a way to precision measurement of the gravitational mass M