Measuring Gravitational Mass of Antihydrogen via Spectroscopy & Interferometry of Gravitational Quantum States

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Physique quantique et applications

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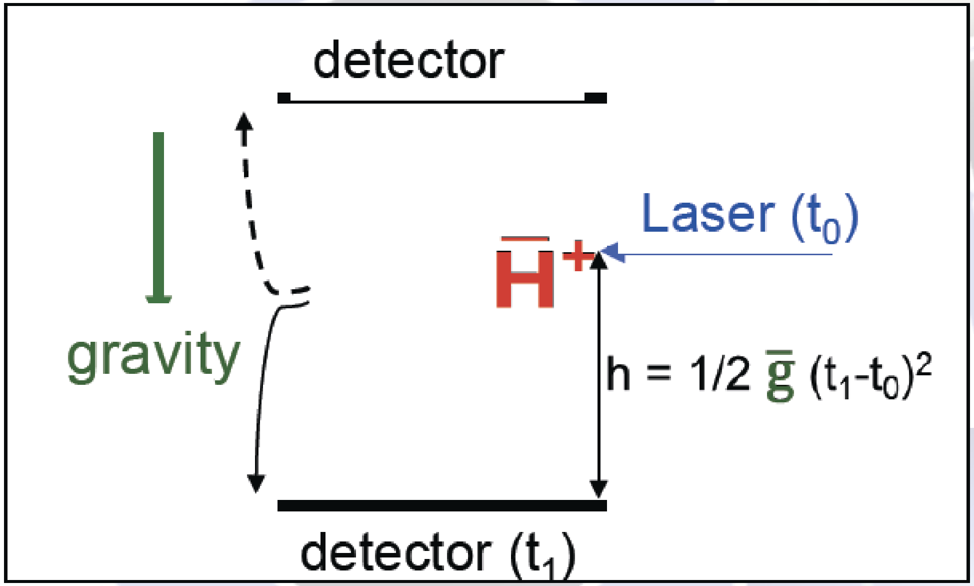
NEUTRONS FOR SCIENCE®

Plan of the talk

- Gravitational states of antihydrogen? One dimensional trap for antihydrogen -now with 17 times longer lifetime
- Spectroscopy and Interferometry of Gravitatioanal Quantum states
- Gravitational mass measurement with gravitational states

Gbar Experiment

principle



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

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

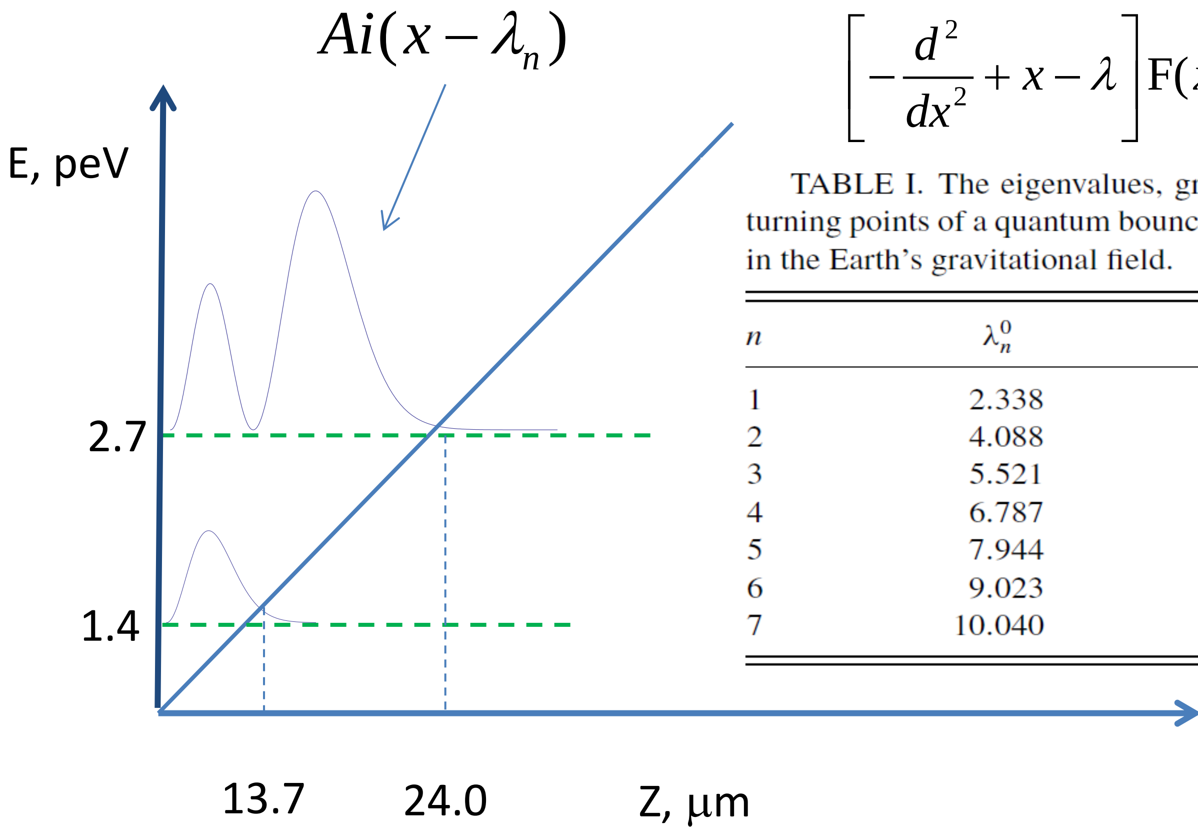
Velocity fluctuation	100 m/s	3 m/s	0.1 m/s
Temperature equivalent	1 K	1 mK	1 μK

Desired range

Gravitational quantum states?

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

Nature 415, 297 (2002)



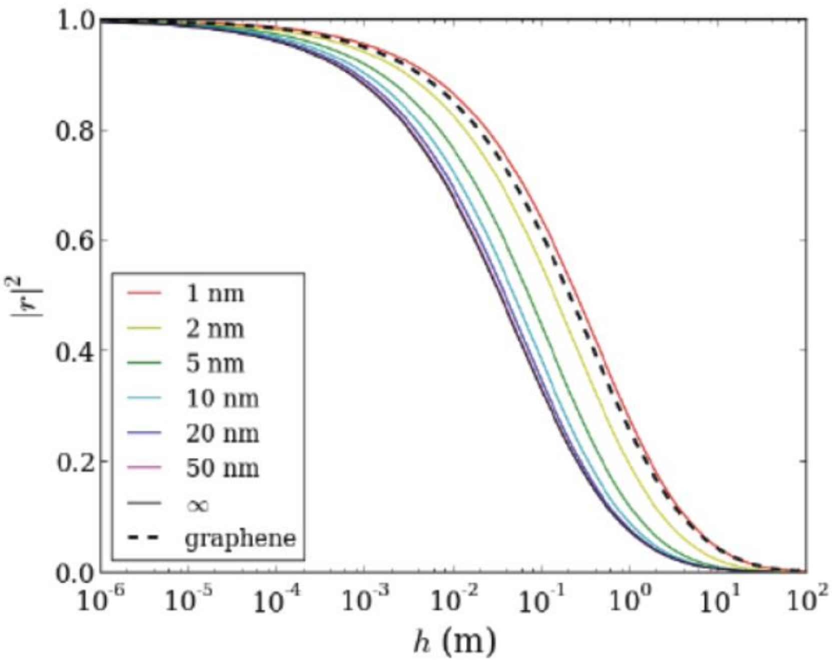
$$\left[-\frac{d^2}{dx^2}+x-\lambda\right]F(x)=0,\; F(0)=0$$

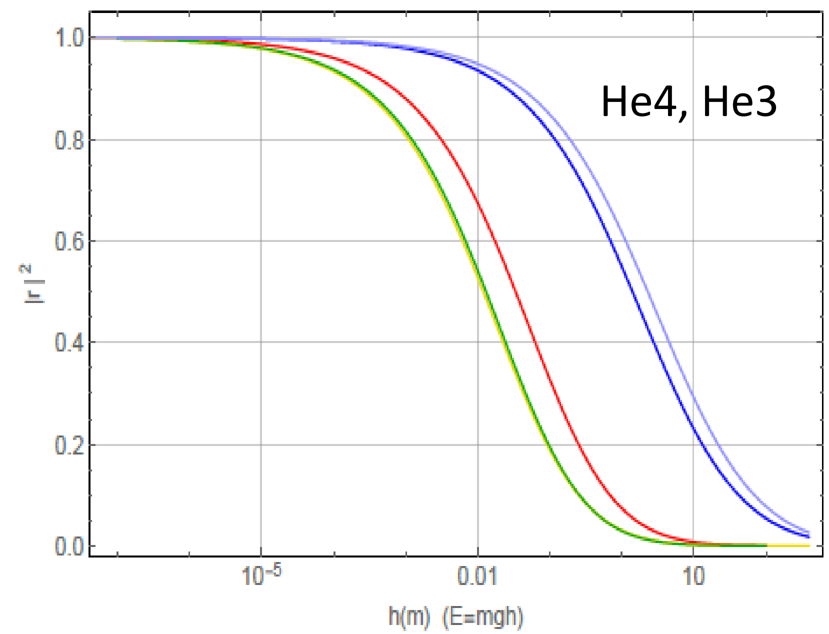
TABLE I. The eigenvalues, gravitational energies, and classical turning points of a quantum bouncer with the mass of (anti)hydrogen in the Earth's gravitational field.

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

Quantum reflection from material surface

REFLECTION COEFFICIENT





Physical Review A 87, 012901 (2013).

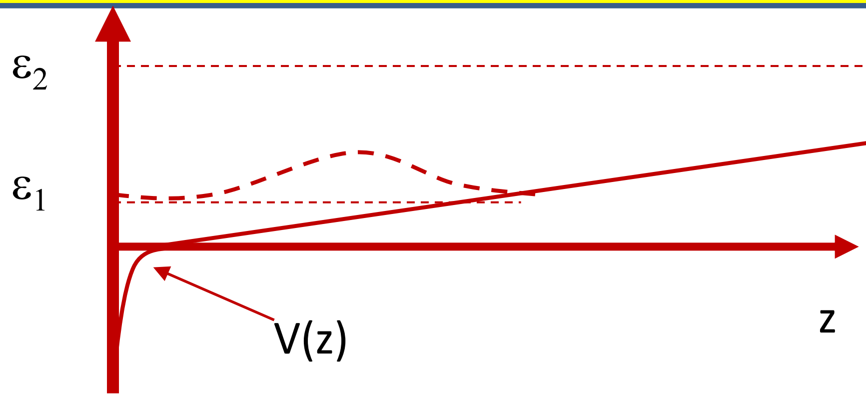
Lifetimes

Ultracold antihydrogen is reflected from material surfaces and can survive on the surface up to few seconds

d (thickness)	t (s), Silicon	t s), Silica
1 nm	0.34	0.61
2 nm	0.25	0.46
5 nm	0.19	0.33
10 nm	0.16	0.27
20 nm	0.15	0.24
50 nm	0.14	0.22
∞	0.14	0.22

Liquid He3 bulk – lifetime 1.7 s !

Correction by Casimir-Polder potential + annihilation



$$\left[-\frac{d^2}{dx^2}+x-\lambda_n\right]\Psi(x)=0$$

$$|a|/l_0 \approx 0.0003 \text{ for } He^3 \text{ bulk}$$

$$\frac{\Psi(0)}{\Psi'(0)} = -\frac{a_{CP}}{l_g} \approx i0.0003$$

Correction by Casimir-Polder and annihilation:

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

$$\varepsilon_n = \varepsilon_0(\lambda_n + \mathrm{Re}\, a/l_g) \quad \Gamma = 2\varepsilon_0 \left|\mathrm{Im}\, a\right|/l_g$$

$$\tau = \frac{l_g}{\varepsilon_g}\frac{\hbar}{2\left|\mathrm{Im}\, a\right|} = \frac{\hbar}{2Mg\left|\mathrm{Im}\, a\right|} \approx 1.7s$$

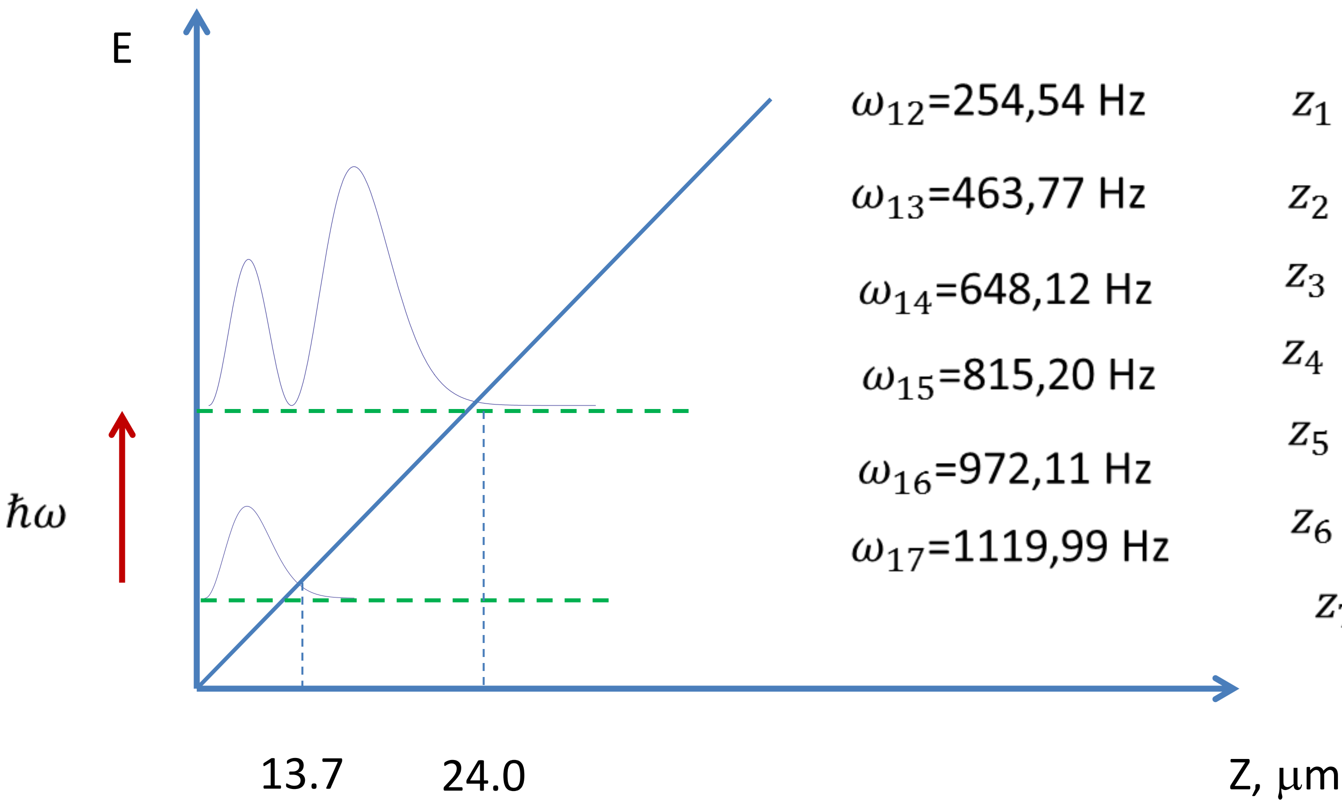
All states have equal shift and lifetime $\Rightarrow$

No surface effects in transition frequencies

Phys. Rev. A 83, 032903 (2011)

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



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

$z_1 = 13.7\ \mu m$

$z_2 = 24.0\ \mu m$

$z_3 = 32.4\mu m$

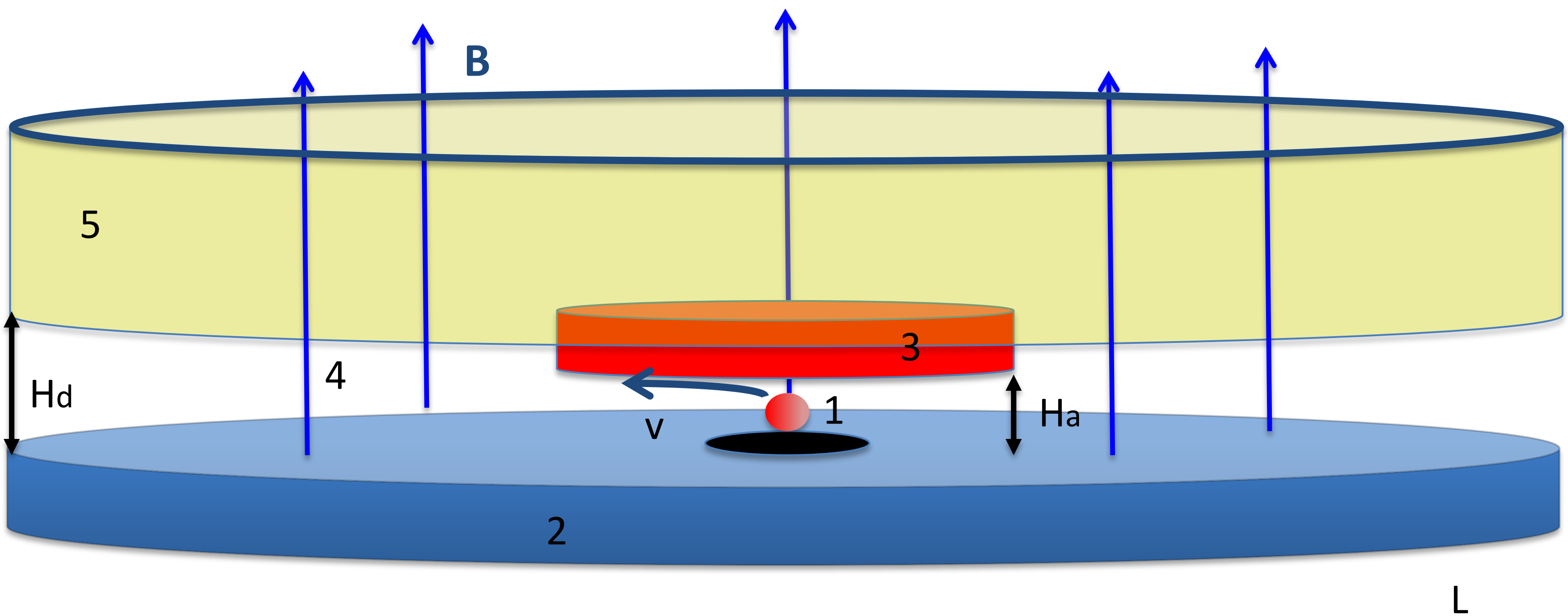
$z_4 = 39.8\ \mu m$

$z_5 = 46.6\ \mu m$

$z_6 = 52.9\ \mu m$

$z_7 = 58.9\ \mu m$

Possible scheme of flow-throw experiment



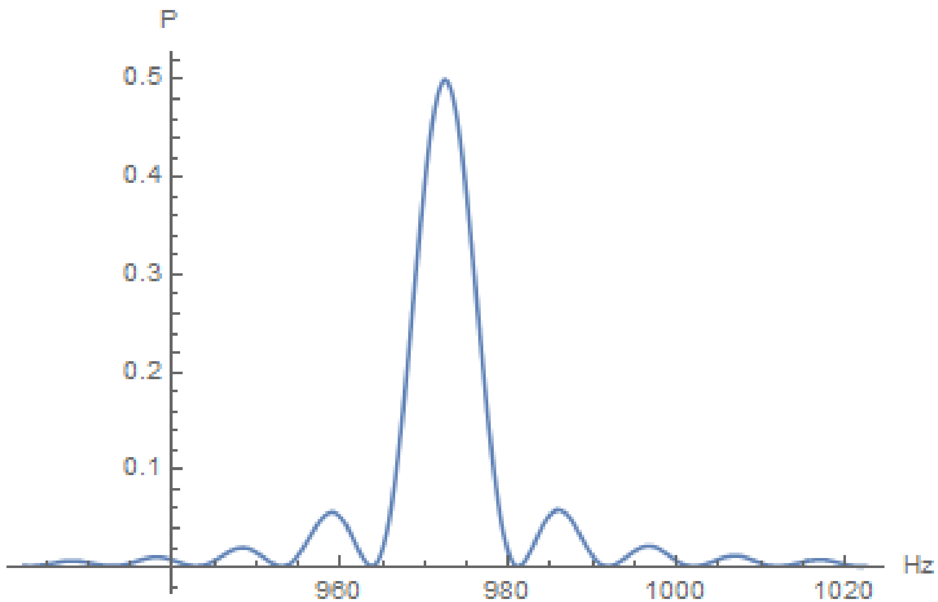
1-source of ultracold antihydrogen, 2-mirror, 3- absorber, 4- magnetic field, 5- detector

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

Transition probability

$$P_{ik} = \frac{1}{2}\frac{\Omega_{ik}^2}{\Omega_{ik}^2 + \hbar^2\Delta^2}\sin^2\left(\frac{t}{\hbar}\sqrt{\Omega_{ik}^2 + \hbar^2\Delta^2}\right)\exp(-\Gamma\, t)$$

$$\Omega_{ik} = \frac{(\mu_B + \mu_{\bar{p}})\beta l_g^3}{\hbar(z_k - z_i)^2}$$

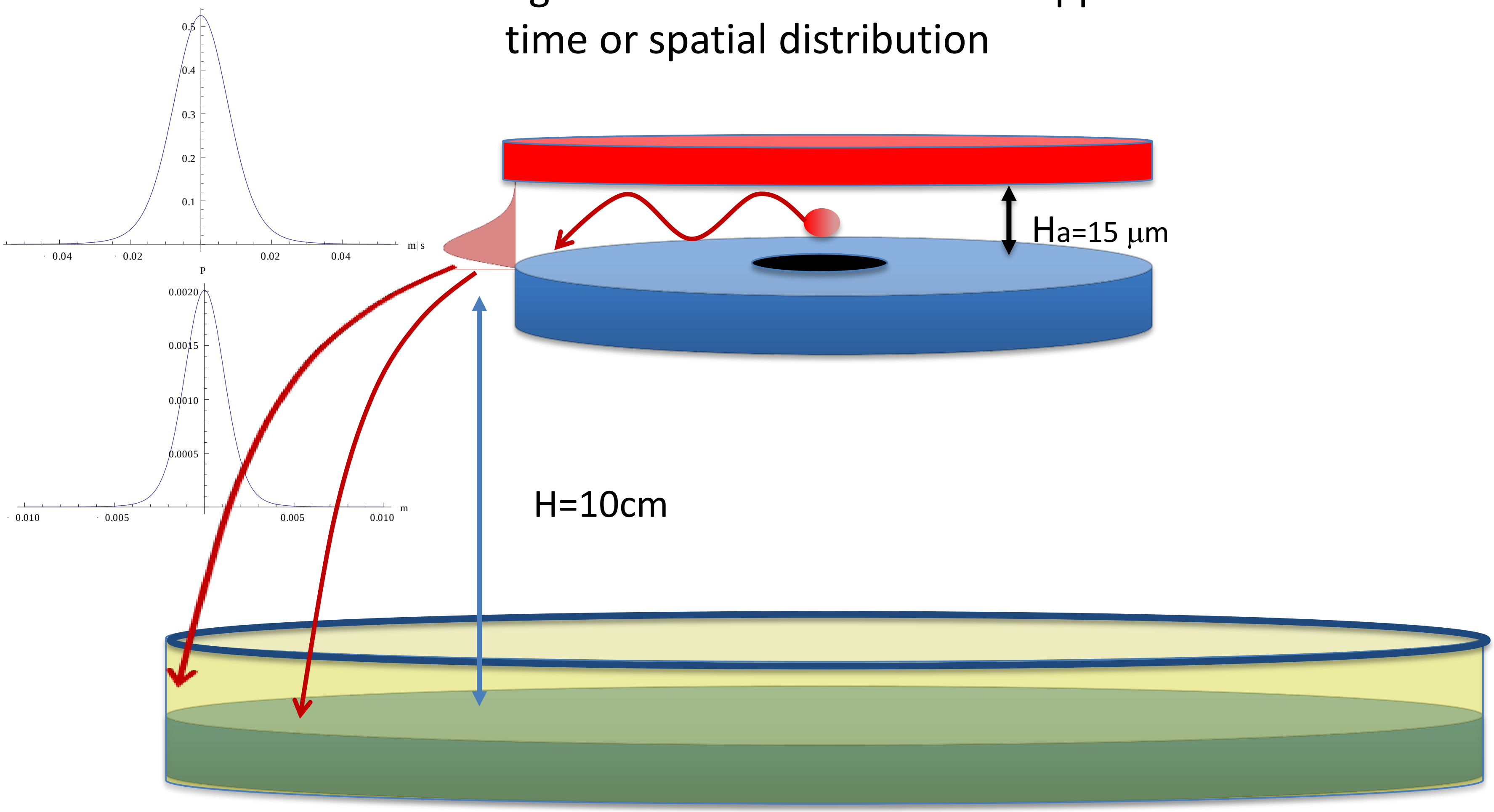


Transition probability as a function of frequency. Transition 1->6

$f_{res} = 972.459$ Hz $\Delta = -0.002$Hz Time of observation t=1 s

Time and Spatial Resolving of Gravitational States

Momentum distribution of gravitational state can be mapped into measurable time or spatial distribution



Mapping of momentum distribution

$$\Psi(z,t) = \frac{1}{\sqrt{2\pi\hbar}} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} e^{ipz/\hbar} G(p,t,p') F_0(p') dp dp'$$

$$G(p,t,p') = \exp\left[-\frac{it}{2m\hbar} (p^2 - Mgpt + M^2 g^2 t^2 / 3) \right] \delta(p - Mgt - p')$$

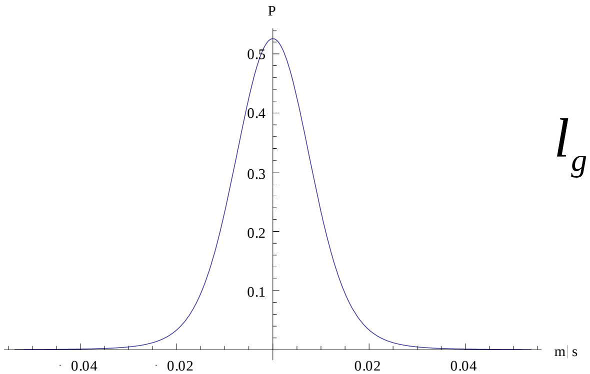
$$\Psi(z,t) \approx \sqrt{\frac{m}{t}} e^{\frac{imz^2}{2t\hbar} + -\frac{it^3 M^2 g^2}{2m\hbar}} F_0(p_0 - Mgt); \; p_0 = (z + \frac{gt^2}{2}) \frac{m}{t}$$

$$|\Psi(z,t)|^2 \approx \frac{m}{t} |F_0(k)|^2$$

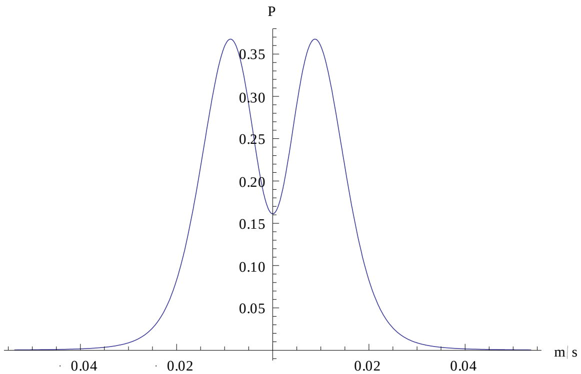
$$1)\, z = z_0 : k = mg(t - t_0), \; t_0 = \sqrt{2g / z_0}$$

$$2)\, t = t_0 = L / v : k = \frac{m(z - z_0)}{t_0}$$

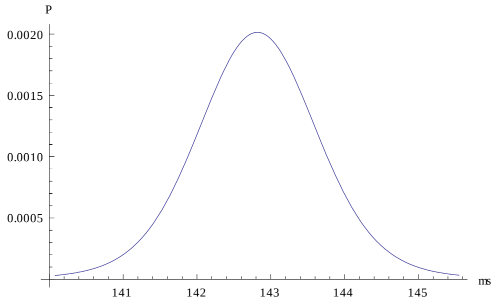
Mapping of momentum distribution into time distribution

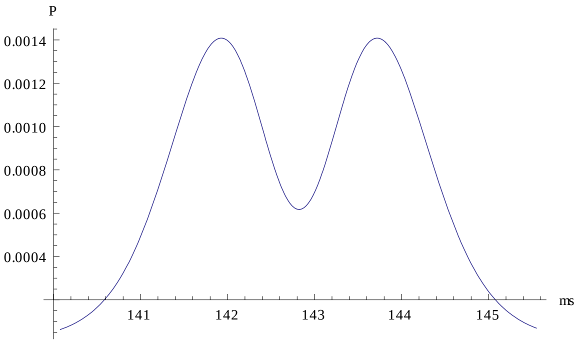


$$l_g = \frac{\delta(n)\hbar}{\Delta k_n}$$

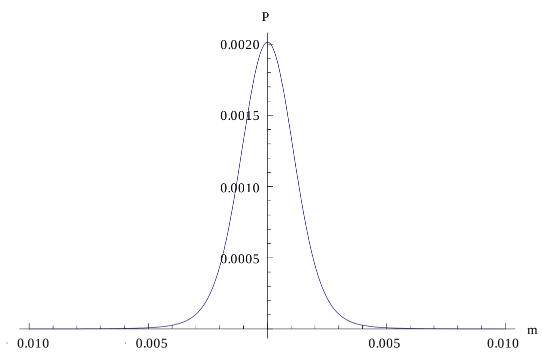


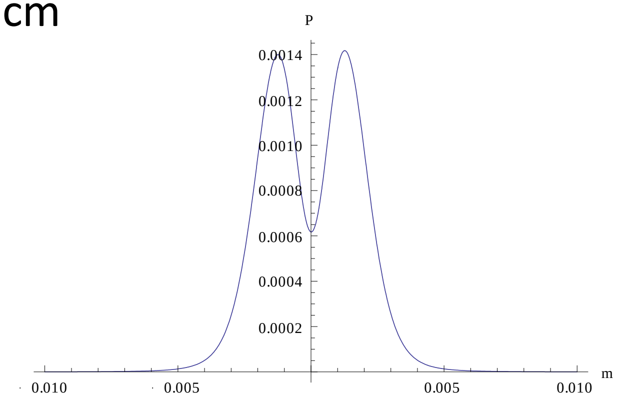
1 state velocity distribution 2 state





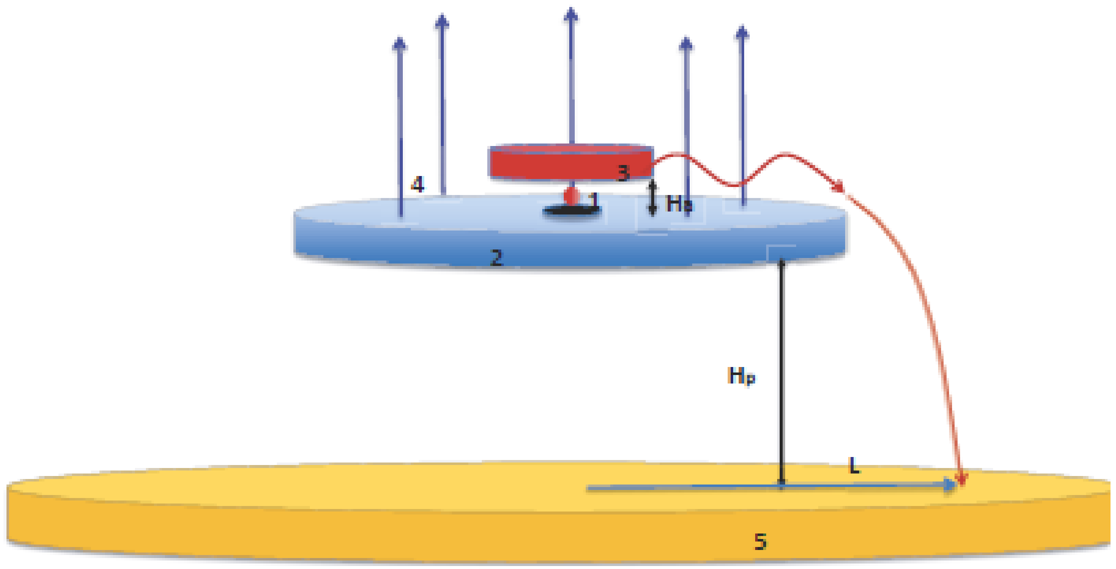
Time-of –fall distribution H= 10 cm

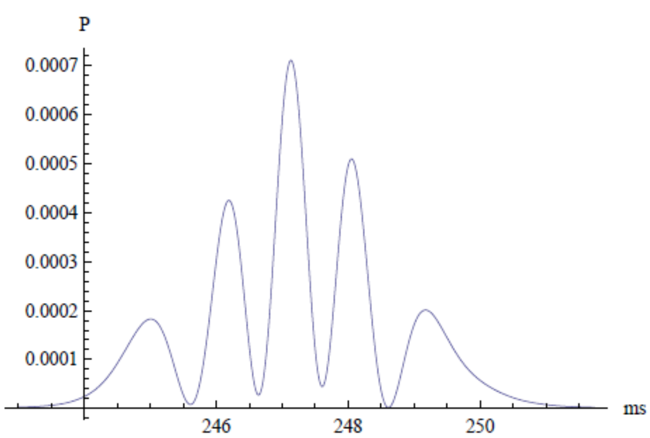


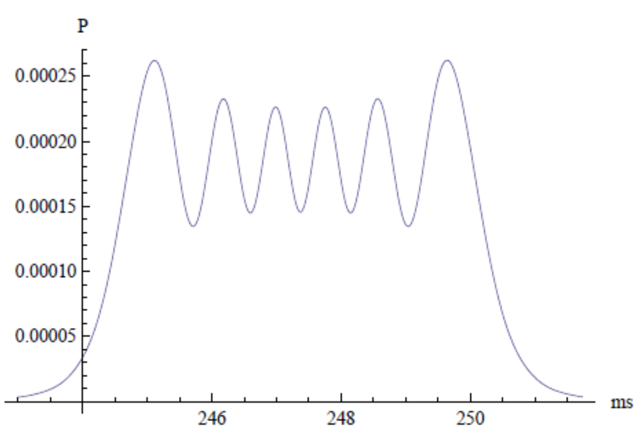


Spatial distribution time-of-flight T=0.1s

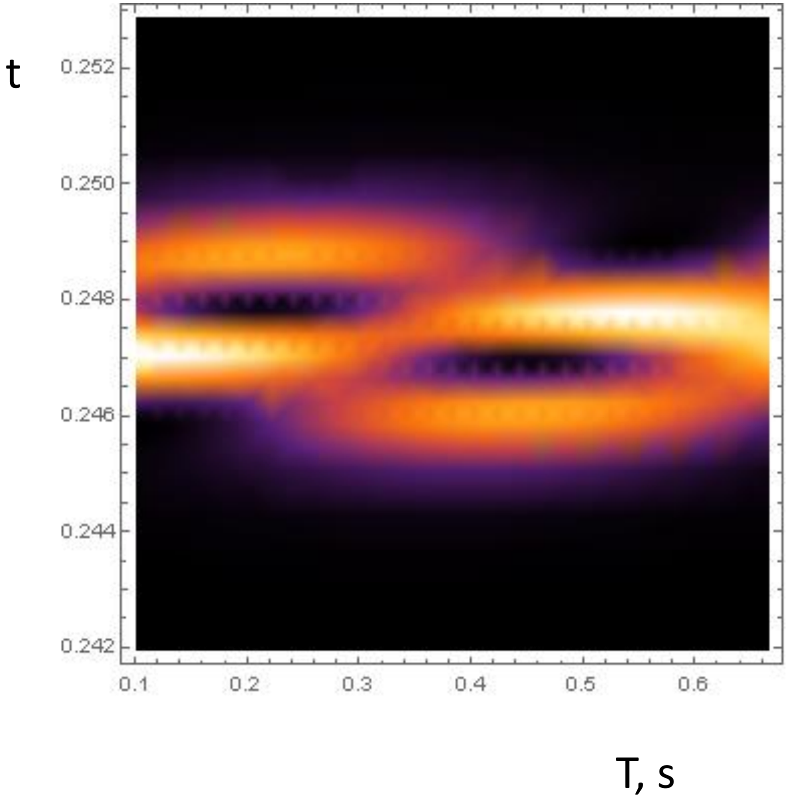
Free-fall of superposition of states



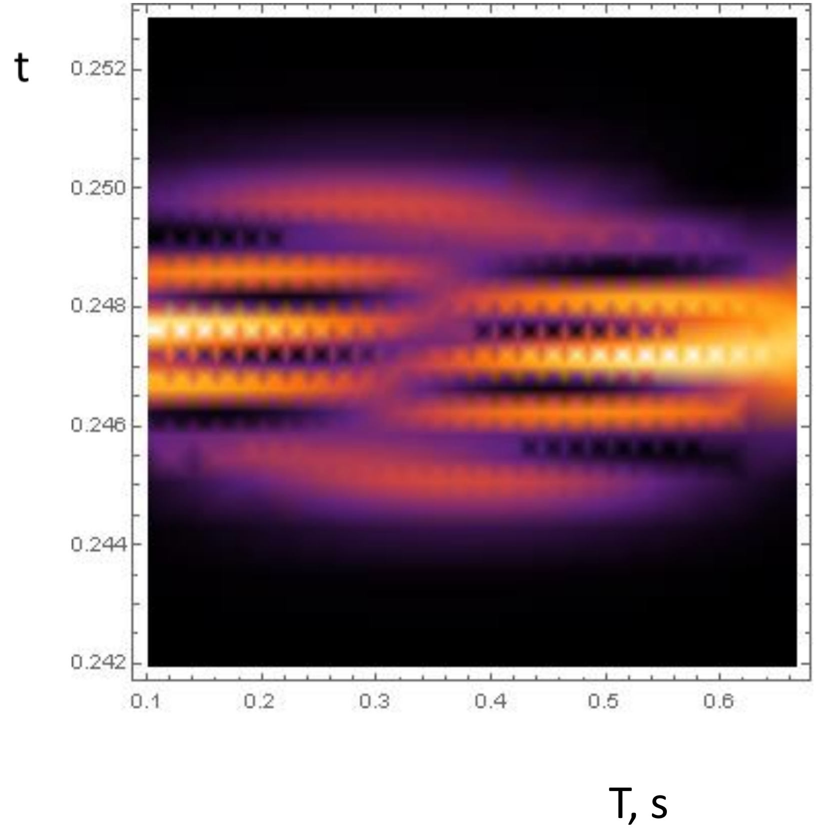




Observation of Interference+ Resonance Transition



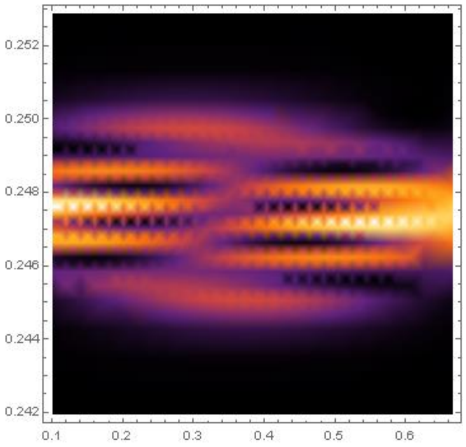
1->3 resonance transition



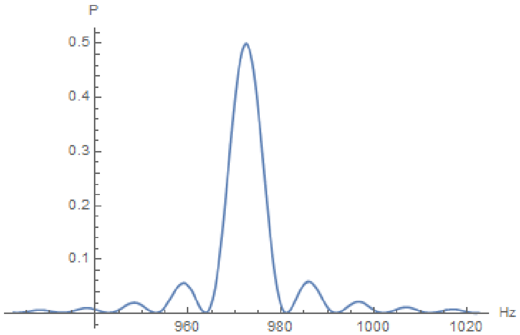
1->6 resonance transition

Gravitational mass

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



$$M = \sqrt{\frac{2m\hbar k_m^3}{g^2(t_m - t_0)^3}}.$$



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

$$\frac{\Delta M}{m} \sim 10^{-4} \quad N = 10^3$$

Conclusions

- Gravitational states of Antihydrogen: simplest bound antimatter quantum system, determined by gravity. Effects of surface are canceled out in the first order (10^{-6} accuracy)
- 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
- Gravitational states are most sensitive to short-range additional to gravity interactions within micrometer range