Snapshots of a Quantum Bouncing Ball realized with the qBounce gravity spectrometer

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AYNN 17.05.2016
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DOKTORATSKOLLEG PI
$\int dk\,\Pi$
Particles and Interactions

NEUTRONS FOR SCIENCE

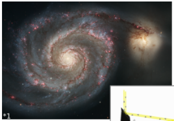
ATOMINSTITUT

Outline

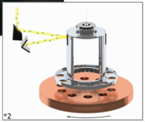
Motivation

qBounce

unique quantum mechanical experiment to explore gravity at short distances (µm)

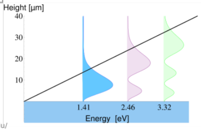


Large scale



Medium scale

Small scale



*1 http://www.spacetelescope.org/images/heic0506a/

*2 http://www.npl.washington.edu/eotwash/sr

contribute to questions on
Dark Matter, Dark Energy,
Fifth Forces, Large extra dimensions,
Torsion, WEP, ...

← **T.Jenke et al., PRL,112 (2014)**

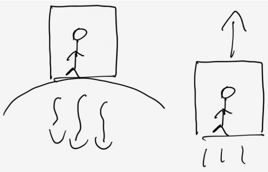
Einstein equivalence principle (EEP)

History of EP: Aristotle, Galileo, Newton

$$m_i a = m_g g$$

General Relativity and EEP

observer can not distinguish between an accelerated reference frame and an reference frame in an gravitational field



UFF or WEP

Weak Equivalence Principle

$\eta = (0.8 \pm 1.8) \times 10^{-13}$

Eötvösh parameter, classical test

LLI

Local Lorentz invariance

tested to a level 10^{-16}

S. Herrmann et al. PRL,95 (2005)

LPI

Local position invariance

tested to a level 10^{-5},10^{-6}

R. Vessot et al. PRL,45 (1980)

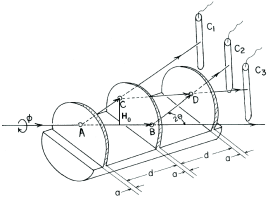
T. Fortier et al. PRL98, (2007)

Quantum mechanical tests of EEP

COW-Experiment

gravitationally induced phase is about 0.8% lower than expected value

K.S.Litrell, B.E.Allman and S.A.Werner, 1997



R.Colella, A,W.Overhauser and S.A. Werner (COW), 1975

Köster

$$\gamma = \frac{m^2}{m_i m_g} \frac{g_{loc}}{g_n}$$

$$1 - \gamma = (1.1 \pm 1.7) \times 10^{-4}$$

J. Schmiedmayer, NIM A 284, (1989) 59

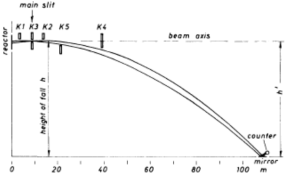


FIG. 1. Principle of the neutron gravity refractometer. $K1, \dots, K5$: slits and stopper for the neutron beam

L.Koester, 1976

Test object neutron

Important properties:

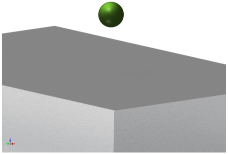
no electric charge: $(-0.4 \pm 1.1) \cdot 10^{-21} e$

extremly small polarizability:

$(11.6 \pm 1.5) \cdot 10^{-4} fm^3 \quad \longrightarrow \propto 10^{-19} \cdot \alpha_{atom}$

magnetic moment:

$\mu_B = -1.913 \mu_N \quad \longrightarrow \propto 10^{-3} \cdot \mu_{atom}$



Ultra-cold neutrons:

kin. energy < 300 neV $\Leftrightarrow$ *velocity* $\leq 8 m/s$

total reflection at any angle of incidence

Gravitationally bound quantum states

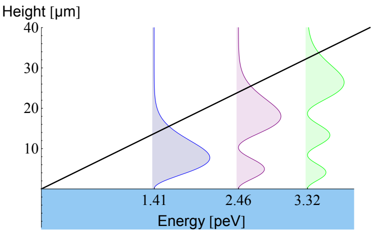
Schrödinger equation

$$\left(-\frac{\hbar^2}{2m_i}\frac{\partial^2}{\partial z^2} + m_g g z\right)\phi_n(z) = E_n \phi_n(z)$$

$$b.c. \quad \phi_n(0) = 0$$

$$\phi_n(z) = a_n Ai\left(\frac{z}{z_0} - \frac{E_n}{E_0}\right)$$

$$z_0 = \sqrt[3]{\frac{\hbar^2}{2m_i m_g g}},\ E_0 = m_g g z_0,\ t_0 = \frac{\hbar}{E_0}$$

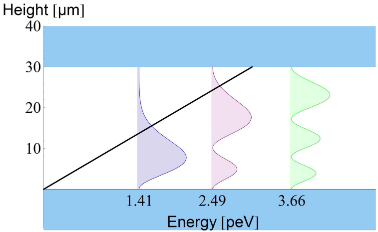


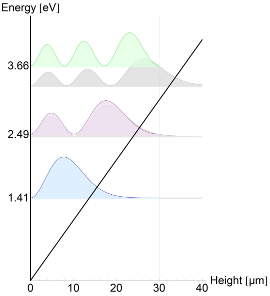
Gravitationally bound quantum states

additional upper mirror:

b.c. $\psi_n(0) = 0 \quad \psi_n(l) = 0$

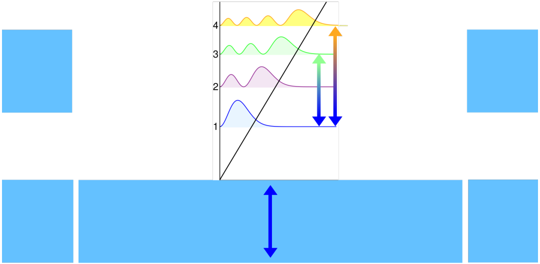
$$\psi_n(z) = c_1 Ai(\frac{z}{z_0} - \frac{E_n}{E_0}) + c_2 Bi(\frac{z}{z_0} - \frac{E_n}{E_0})$$



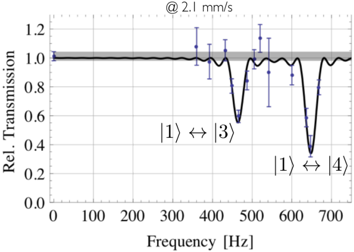


Gravity Resonance Spectroscopy

Rabi-experiment



$$\Delta E_{pq} = h \cdot \nu_{pq}$$

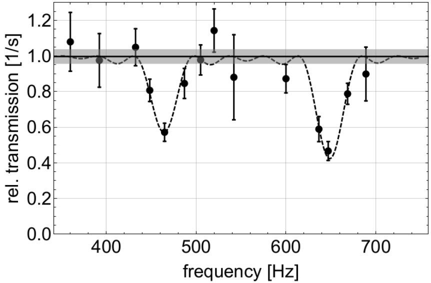


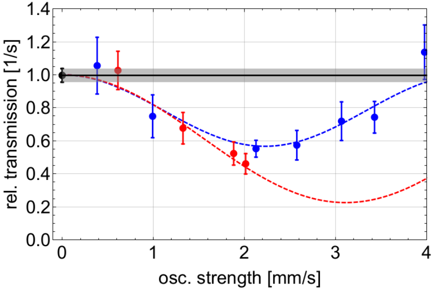
$|1 > \rightarrow |3 >$: 465 Hz
$|1 > \rightarrow |4 >$: 648 Hz

G.Cronenberg, Diss., 2015

Gravity Resonance Spectroscopy

Results GRS measurement 2012 PF2/UCN ILL
Gunther Cronenberg et. al



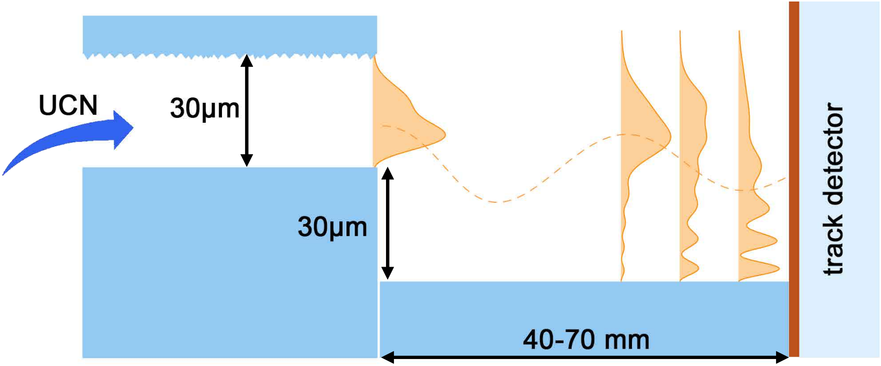


$|1> \rightarrow |3>$: $465.0^{+2.0}_{-2.0}$ Hz

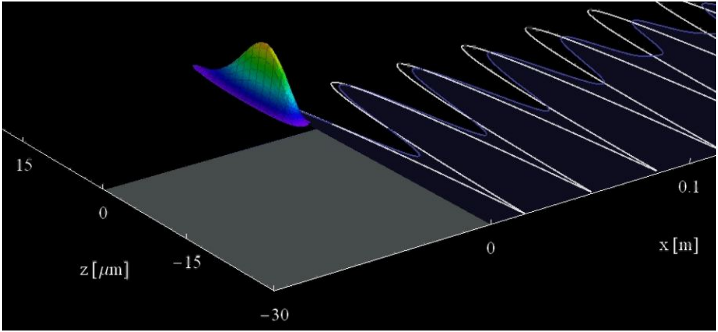
$|1> \rightarrow |4>$: $648.2^{+2.0}_{-2.3}$ Hz

G.Cronenberg, Diss., 2015

Quantum Bouncing Ball



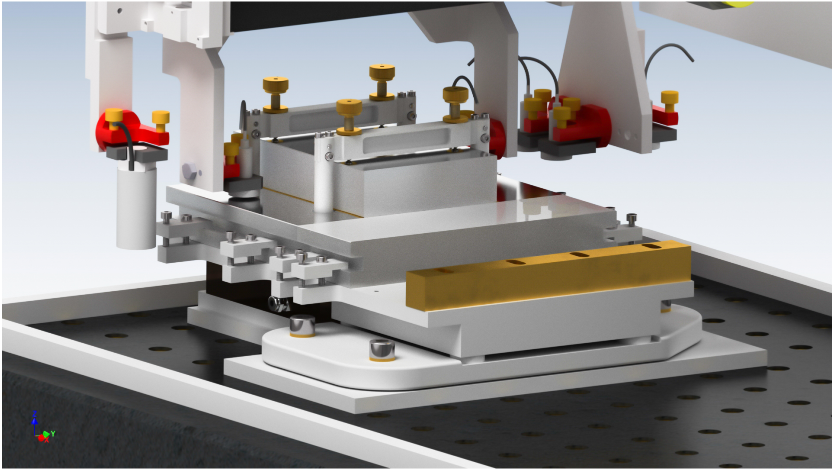
Time evolution movie



Movie

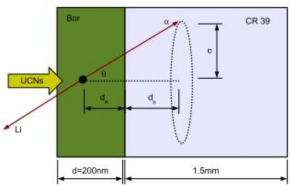
Simulation: Reiter, Schlederer, Seppi

Experimental setup

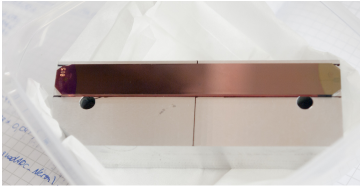


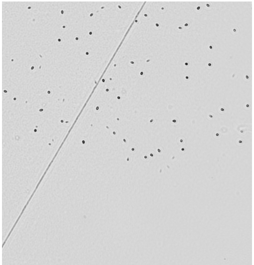
Track detector

$$n + {}^{10}B \rightarrow \alpha + {}^{7}Li^{*} \rightarrow \alpha + {}^{7}Li^{3+} + \gamma \quad (94\%)$$
$$n + {}^{10}B \rightarrow \alpha + {}^{7}Li^{3+} \quad (6\%)$$

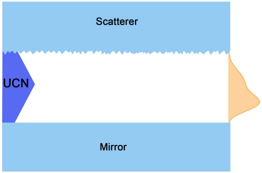


D. Stadler, Diplomarbeit, 2009

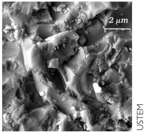


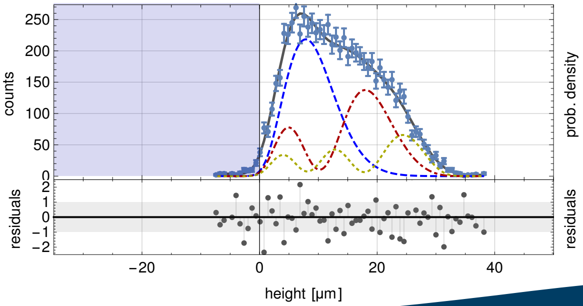


Preparation



Roughness $r_z = 3\ \mu m$





$$|\Psi_I(z, t_1)|^2 = \sum_n |C_n(t_1)|^2 \cdot |\psi_n(z)|^2$$

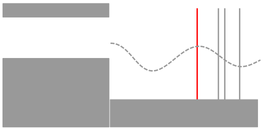
$|c_1|^2 = 45\%$

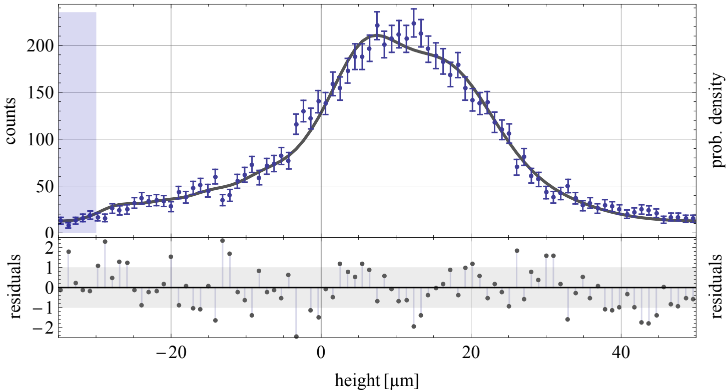
$|c_2|^2 = 36\%$

$|c_3|^2 = 18\%$

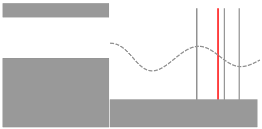
preliminary

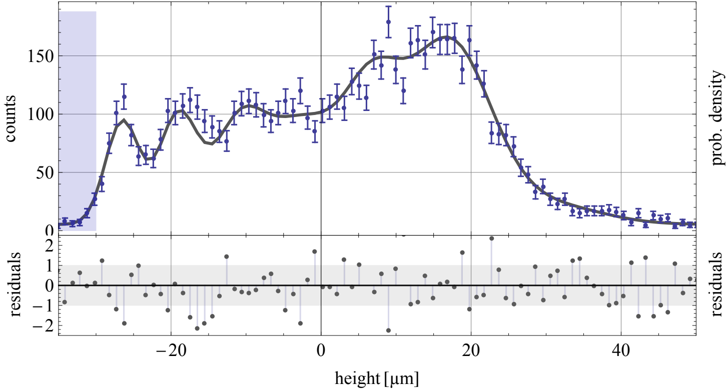
41 mm





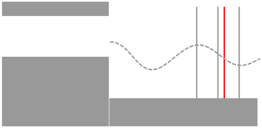
51 mm

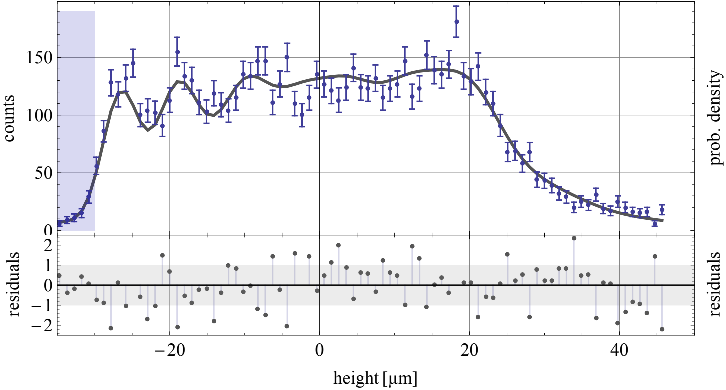




counts
150
100
50
0
prob. density
residuals
2
1
0
−1
−2
residuals
−20
0
20
40
height [µm]

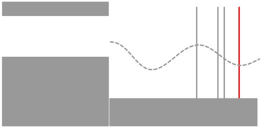
54 mm

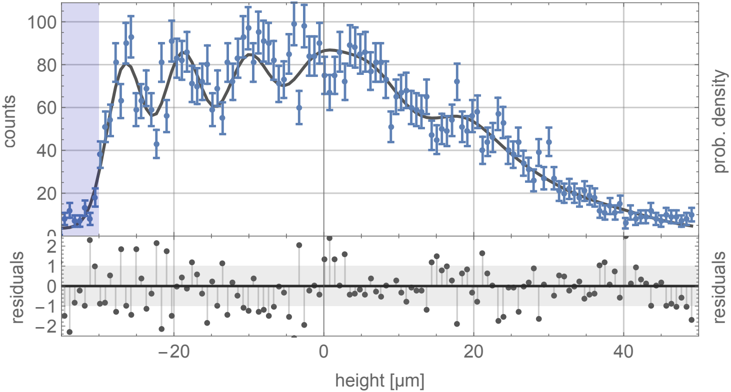




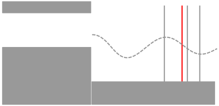
counts
prob. density
residuals
residuals
0
50
100
150
2
1
0
−1
−2
−20
0
20
40
height [μm]

61 mm

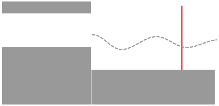


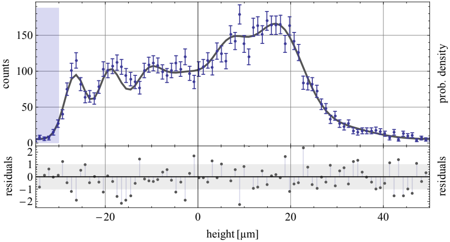


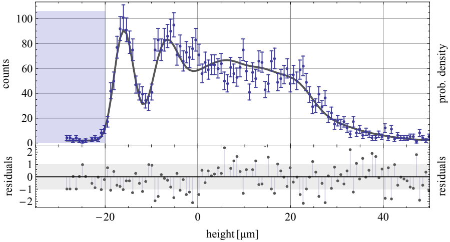
counts
100
80
60
40
20
0
prob. density
residuals
2
1
0
−1
−2
residuals
−20
0
20
40
height [μm]



51 mm







@ 30 μm step

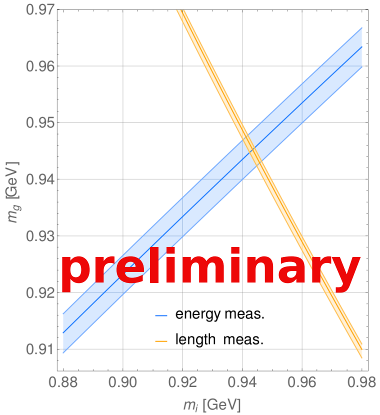
@ 20 μm step

Preliminary results

$$z_0 = \sqrt[3]{\frac{\hbar^2}{2 m_i m_g g}}, \qquad E_0 = m_g g z_0$$

$$m_g = \frac{E_0}{g z_0}, \qquad m_i = \frac{\hbar^2}{2 z_0^2 E_0}$$

$$\frac{m_g}{m_i} - 1 = \text{insert final value}$$



Conclusion

- **qbounce - gravity tests at short distances**
- **WEP, tests of WEP**
- **Gravity Resonance Spectroscopy**
- **Quantum Bouncing Ball**
- **first precision measurement of a Quantum Bouncing Ball**
- **preliminary results**

Team

T. Jenke

T. Rechberger

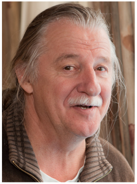
M. Thalhammer

J. Herzinger

G. Cronenberg

T. Putz

M. Stöger



P. Geltenbort

H. Abele

H. Filter

Thank you!