# Snapshots of a Quantum Bouncing Ball within the qBounce project

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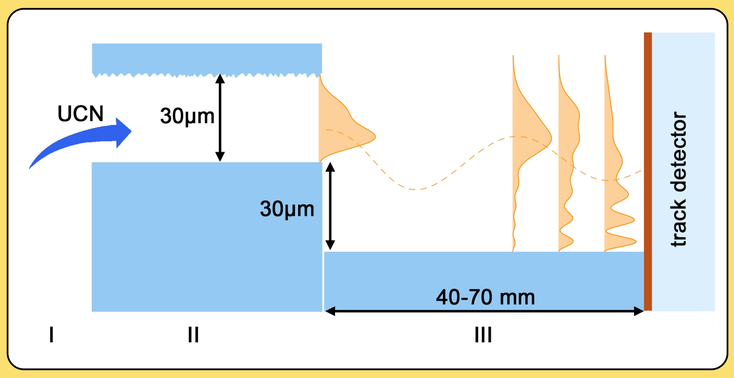
*One class of gravity experiments within the qBounce project focuses on the realization of a Quantum Bouncing Ball, i.e. a measurement of the time evolution of a neutron bouncing above a horizontal plane. In 2014, the spatial probability distribution of this Schrödinger wave packet has been measured for different observation times with a spatial resolution of about 1.5µm.*
*We illustrate the role of interference weaving the quantum carpet of several quantum states: After a first quantum reflection, several snapshots show the fall and the rise of the wave packet. The data may be used to test the Weak Equivalence Principle (WEP) in the quantum regime.*

## Airy functions in the linearized gravitational potential

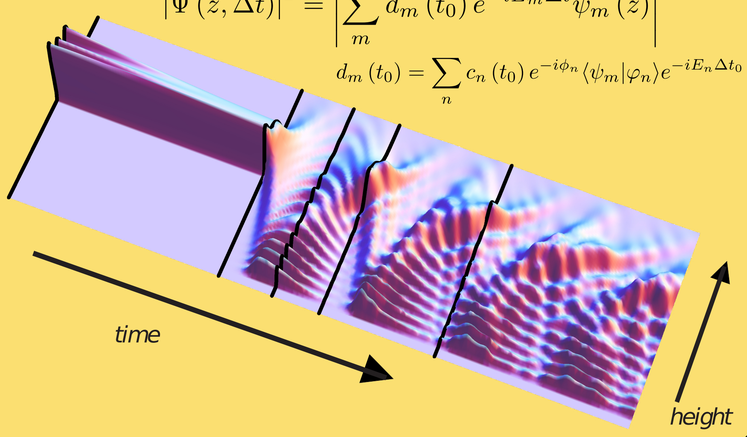



*The free fall of a quantum mechanical wave packet in a linear potential shows interesting physical properties and phenomena like the collapse and revival of the wavefunction. The time evolution of the wave function shows a typical pattern, the so-called quantum carpet, which is visualized in the figure below.*
*As the inertial and gravitational mass enter Schrödinger's equation with different powers, the measurements may be used to perform tests of the WEP in the quantum regime, conceptionally different from classical tests.*

$$|\Psi(z,\Delta t)|^2 = \left|\sum_m d_m(t_0)\, e^{-iE_m\Delta t}\psi_m(z)\right|^2$$

$$d_m(t_0) = \sum_n c_n(t_0)\, e^{-i\phi_n}\langle\psi_m|\varphi_n\rangle e^{-iE_n\Delta t_0}$$

*Ultracold neutrons form bound states in the Earth's gravitational field. In the last 15 years, a series of experiments studied these states. One result was the realization of a resonance spectroscopy method without the need of any electromagnetically interacting fields. The measured transition frequencies were used to constrain Dark Matter and Dark Energy scenarios. In a recent experiment, we dropped a well-prepared wave-packet of such states a step of some tens of microns, let the wave packet evolve in time, and measured the spatial probability distribution using track detectors.*




## The probe: Ultracold neutrons...

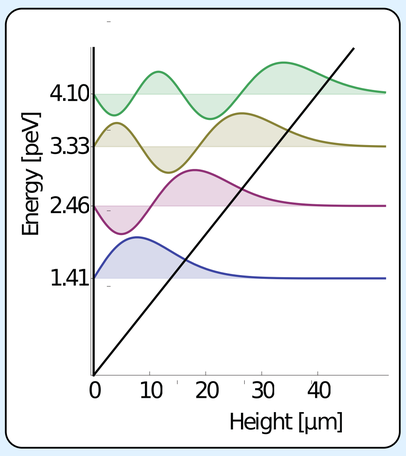
*... are neutral: $\delta q < 10^{-21}\, q_e$,*
*... are hardly polarizable*
*$\alpha = (11.6 \pm 1.5)\, 10^{-4}$ fm,*
... are long-living $\tau \approx$ *15 min,*
... are rather slow $v \approx$ *6 m/s*

*and are therefore ideal candidates for precision gravity experiments at short distances.*

*For our experiments we use the world's strongest continuous ultracold neutron source PF2 at the Institut Laue-Langevin in Grenoble/France.*

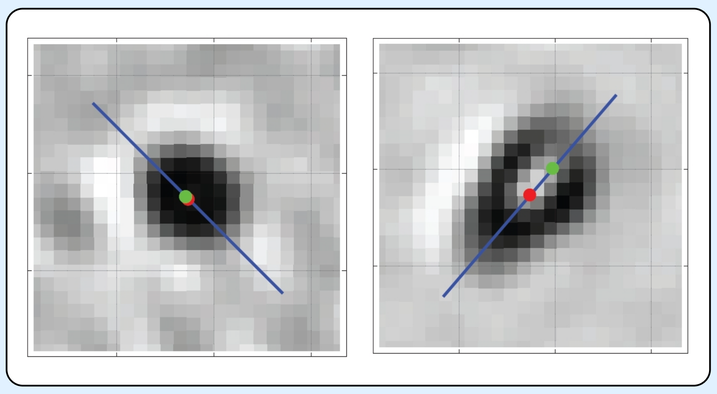
## Gravitationally Bound Quantum States of UCN

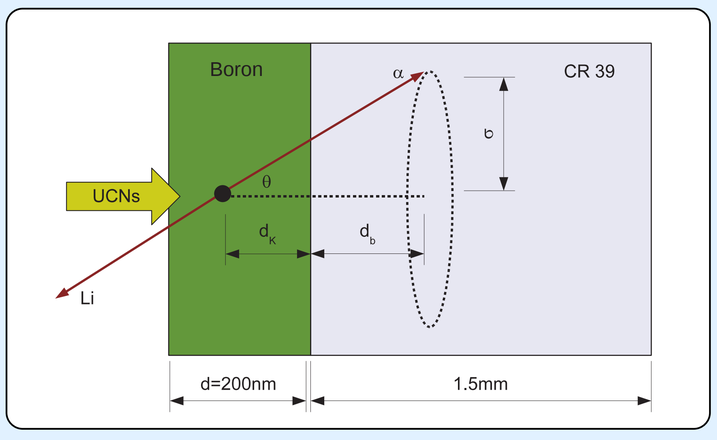
*Above a horizontal mirror, ultracold neutrons form quantum states in earth's gravitational field with eigen-energies in the pico-eV-regime and a typical size of a few ten microns. The states may be tuned by a second horizontal neutron mirror on top at a height h, which defines a second boundary condition.*




## Track Detector & Read-out

*High spatial resolution can be achieved by placing a polymer (CR39) behind a thin boron layer. The fission particles cause defects in the polymer which can be read out with a microscope after an etching process.*



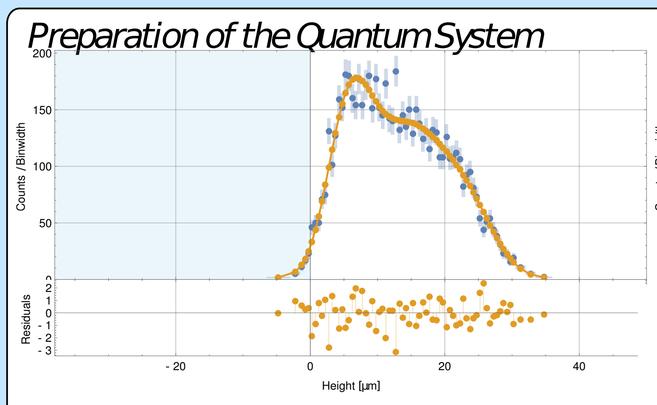



*The resulting spatial resolution of around 1.5 µm depends on the etching process and the boron layer thickness. It may be improved by a reconstruction of the track. The efficiency of around 40% is due to a maximum detection angle θ of about 70°.*

## Quantum Bouncing Ball Measurements

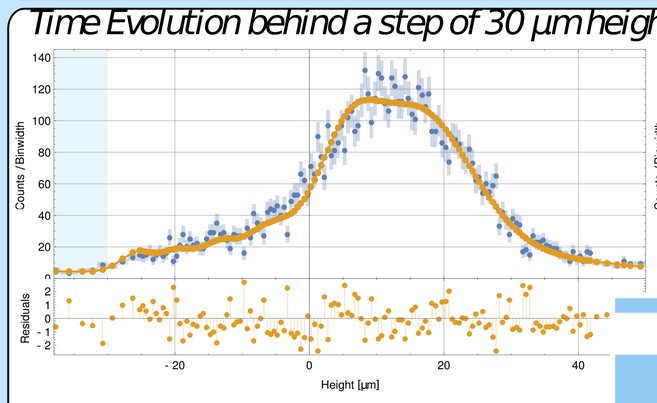
### Preliminary Experimental Results

#### Preparation of the Quantum System

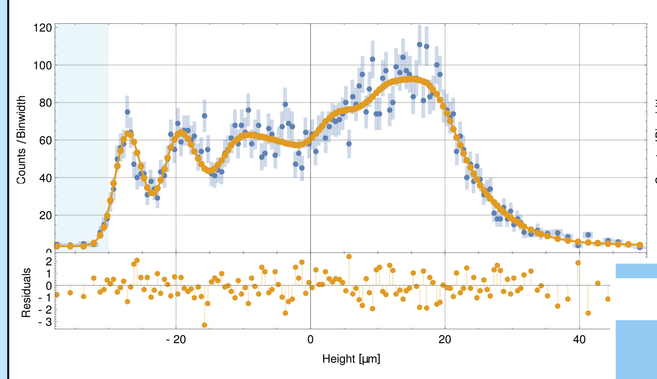



*A 15cm long neutron mirror - scatterer - system of 30µm slit width prepares the neutrons into a superposition of the lowest gravitationally bound states.*

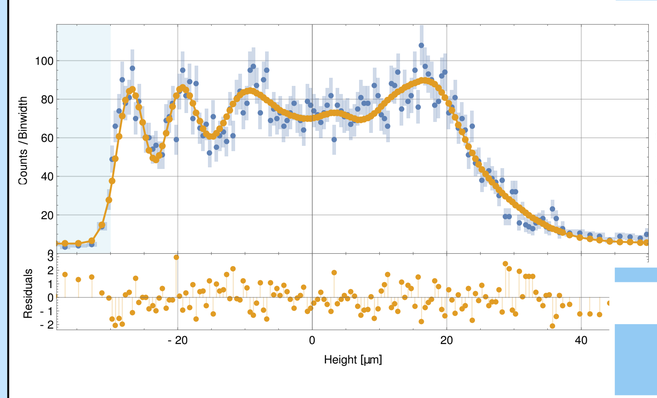
#### Time Evolution behind a step of 30 µm height



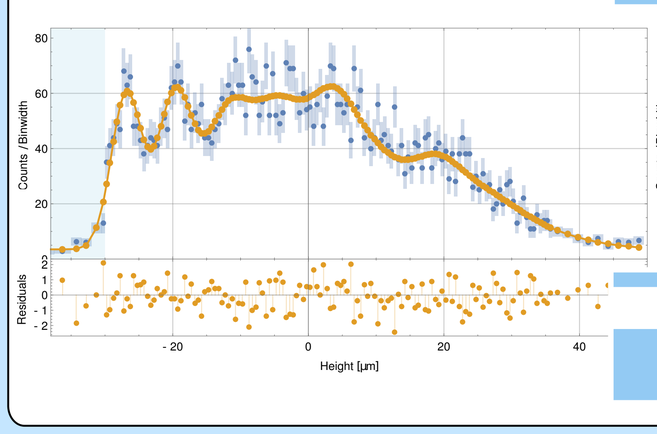

*At 41mm behind the step, the wave packet reaches its upper turning point after the first quantum reflection. Here, the z-expectation value is maximal.*




*At 51mm behind the step, we clearly resolve the quantum carpet (see Fig. of the simulation).*

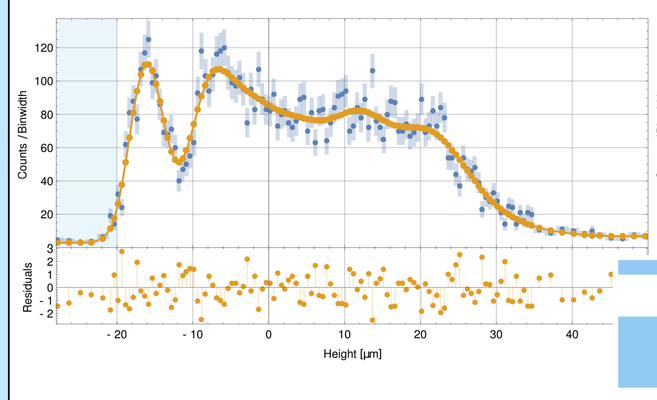



*At 54mm behind the step, the wave packet is close to the point of the second quantum reflection.*




*At 61mm behind the step, the wave packet is at the point of the second quantum reflection.*

#### Time Evolution behind a step of 20 µm height




*A reduction of the step height to 20µm increases the contrast of the quantum carpet to approx. 50%. The snapshot was taken 51mm behind the step.*

## For inquiring minds...

*... Gravitationally bound quantum states of UCN exist! Nesvizhevsky et al., Nature 415, 297 (2002).*

*... How to build detectors with micron spatial resolution: Jenke et. al., NIM A732, 1-8 (2013).*

*... On Gravity Resonance Spectroscopy (GRS): Jenke et al., Nature Physics 7, 468-472 (2011).*

*... GRS constrains. Dark Matter and Dark Energy Scenarios: Jenke et al., Phys. Rev. Lett. 112, 151105 (2014).*

## Acknowledgements

FWF *No. I529-N20, I531-N20, I862-N20, P26781-N20*
Der Wissenschaftsfonds.
Doktoratskolleg Particles and Interactions
DFG *Priority Programme (SPP) 1491*
ANR *2011-ISO4-007-02*