Realization of a Quantum Bouncing Ball Gravity Spectrometer

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Abstract

The ***q*Bounce**-experiment investigates gravity at small distances using high precision, frequency based measurement methods of quantum mechanics. **Ultracold neutrons** (UCNs) form macroscopic bound states above a flat surface in the gravity potential of the Earth, building the connection between quantum mechanics and gravity. Exploiting this feature and based on first measurements of those states, we performed various measurements of the so-called Quantum Bouncing Ball and developed techniques for **Gravity Resonance Spectroscopy** (**GRS**) [1, 2].
In this poster, we present the ongoing development of GRS, namely the **application of Ramsey's method of separated oscillating fields to gravitationally bound UCNs [3].**
This experiment is to be realized from beginning of November 2016 at the Institut Laue-Langevin.

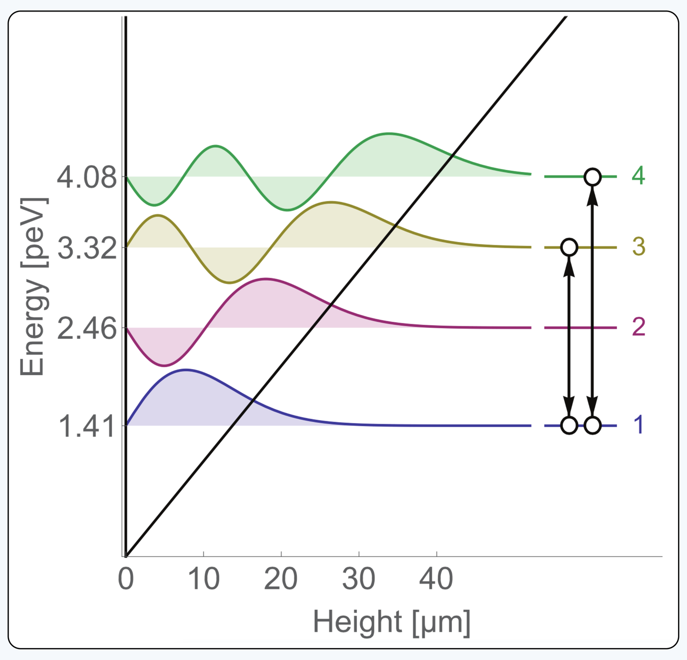
Motivation

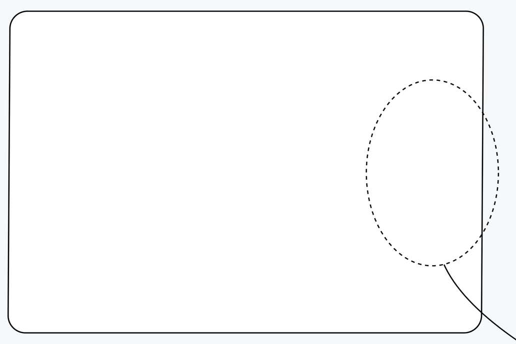
- We present the neutron both, as a measuring tool and as an object for gravity research.
- It gives access to all gravity parameters: distance, mass, energy, momentum and torsion.
- Spectroscopy methods have shown spectacular sensitivity in the past.
- Neutrons are an ideal tool to study gravity as they widely bypass electromagnetic background.
- This setup can be adapted for probing the neutron's electric charge.

Ultracold neutrons form **eigenstates** (colored curves) in the gravity potential of the earth:

$$V(z) = mgz$$
$$\Psi_n(z) = c_n\, Ai\left(\frac{z}{z_0} - \frac{E_n}{E_0}\right)$$

Airy functions *Ai*: Solutions of Schrödinger equation for neutron in height *z* in linear potential





State preparation:
UCNs are totally reflected from flat surfaces (mirror) and scattered from rough surfaces (scatterer). Therefore higher states are suppressed with a mirror alignment shown on the left.
This principle is used in Region I & V below.

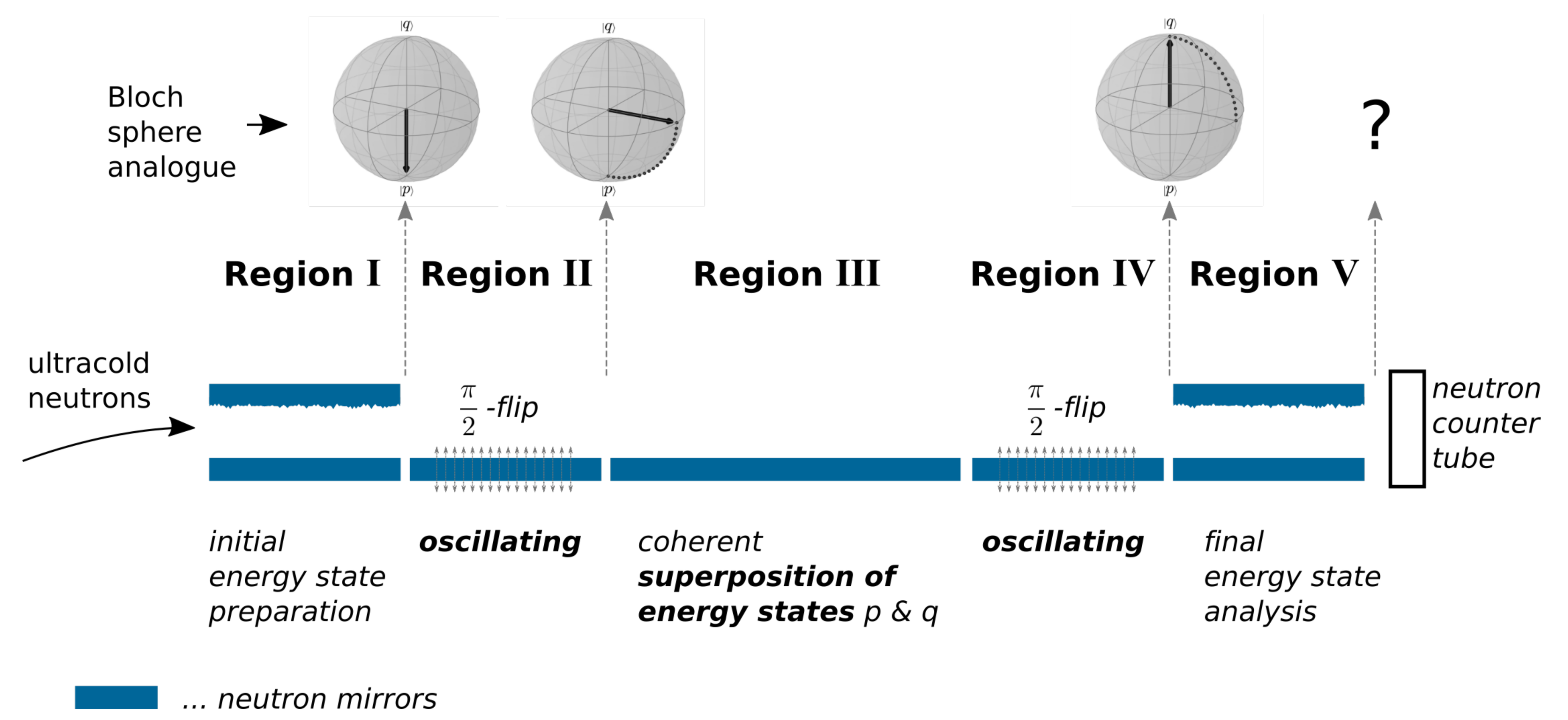
Ongoing: Ramsey's method within Gravity Resonance Spectroscopy

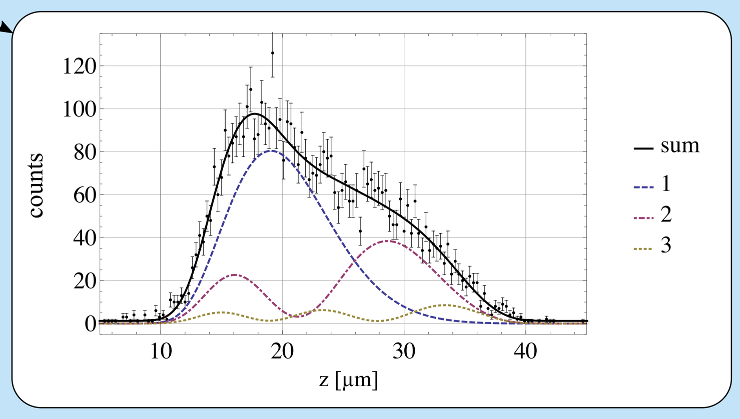
Region I / V
State selector / analyser - higher energy states get scattered out of the system by upper mirror (see top right box)

Region II / IV
Transitions between gravitational quantum states as neutrons couple to the mechanically driven harmonic **oscillations of the mirror**

Region III
Phase evolution of the coherent superposition of two eigenstates
(Higher resolution with increasing length!)

Driving transitions of gravitational quantum states of UCNs by coupling to a *mechanical* oscillator, no light and no spin involved here!



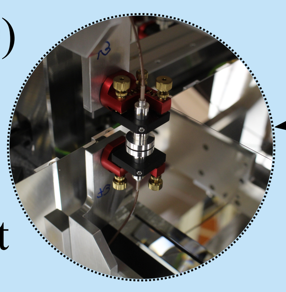


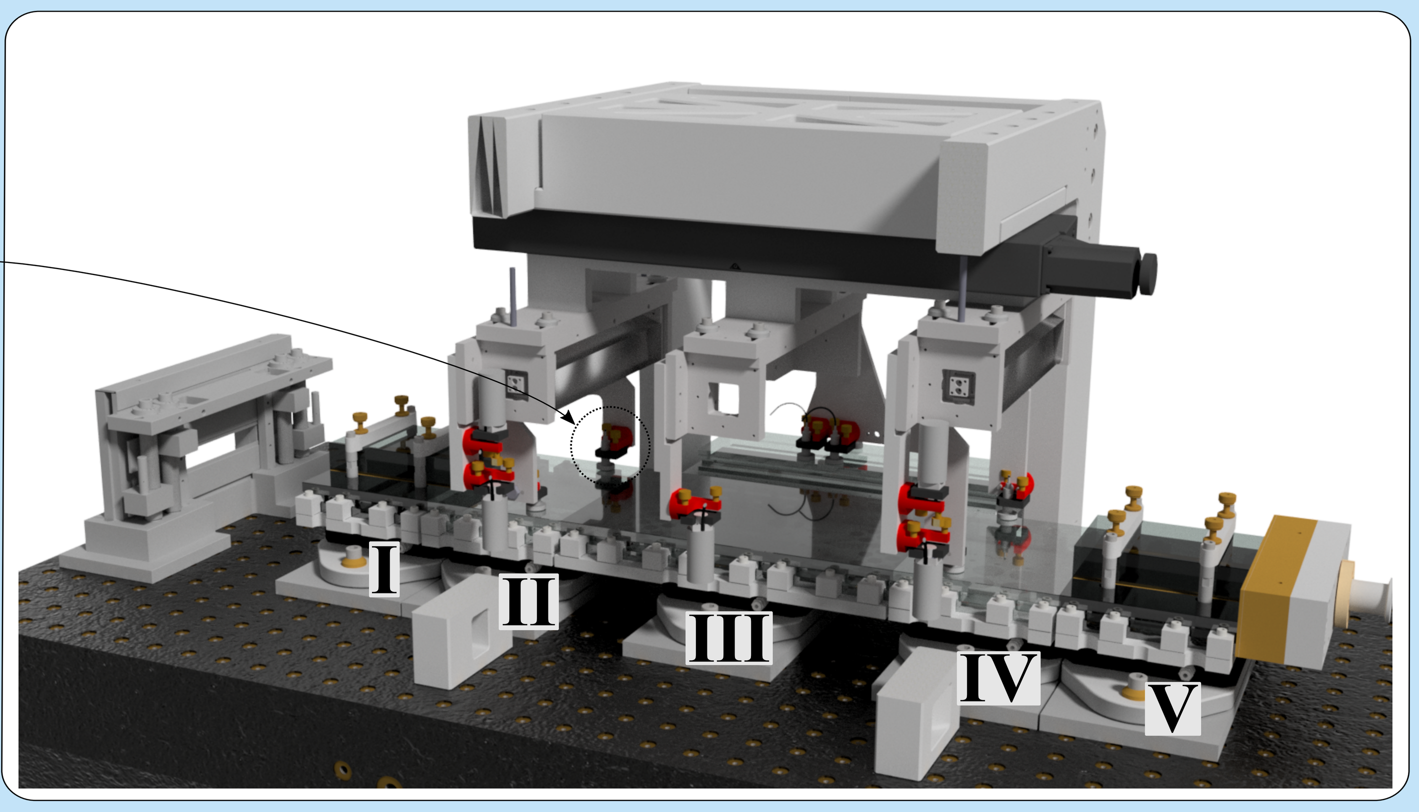
Previously Observed Transitions:
With well prepared energy eigenstates specific transitions between two states can be driven. Several transitions have been observed and their energy difference measured:

|1⟩ ↔ |2⟩
|1⟩ ↔ |3⟩
|1⟩ ↔ |4⟩
|2⟩ ↔ |3⟩
|2⟩ ↔ |4⟩

Oscillation frequencies from ~150 Hz up to ~1000 Hz can be applied to regions II & IV.

- vacuum ($\leqq 10^{-4}$ mbar)
- magnetic shielding (suppression factor 80-100)
- leveled measuring plate (acc. ~ 100 nrad)
- mirror-to-mirror alignment (acc. ~ 500 nm)
- neutron counter tube: efficiency 77% background $(0.63 \pm 0.03) \times 10^{-3}\,s^{-1}$
- projected sensitivity: first round: 10^{-16}eV, long term: 5×10^{-21}eV

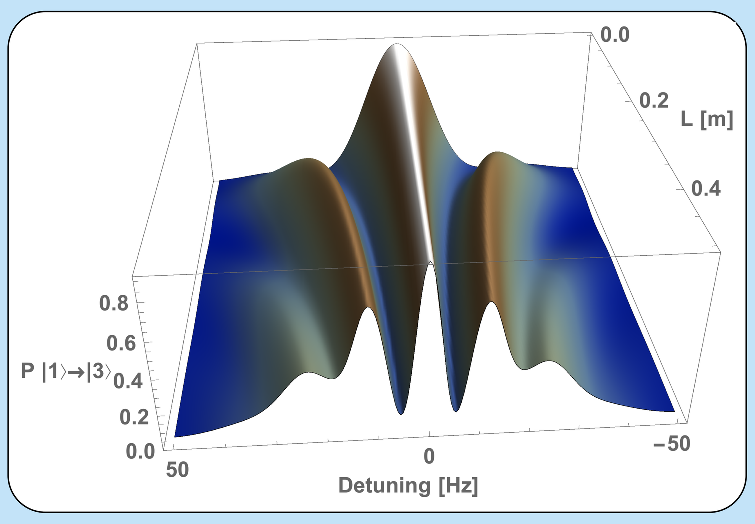




- Ramsey fringes show self-focusing effect for broader velocity spectrum due to separated interaction regions
➔ higher countrate possible

- Setup adjustable for probing the neutron's electric charge [4], for storing neutrons in the middle region and for measuring spin-dependently

From Rabi to Ramsey:
Expected transition probability for |1⟩↔|3⟩ with varying length L of Region III, detuning from the transition frequency and smeared out higher order fringe pattern.

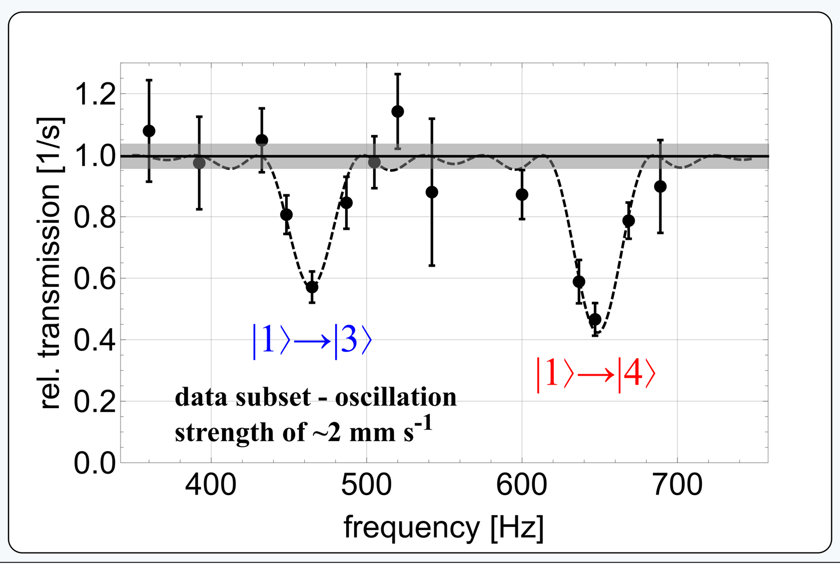


Previous Realization of Rabi's method

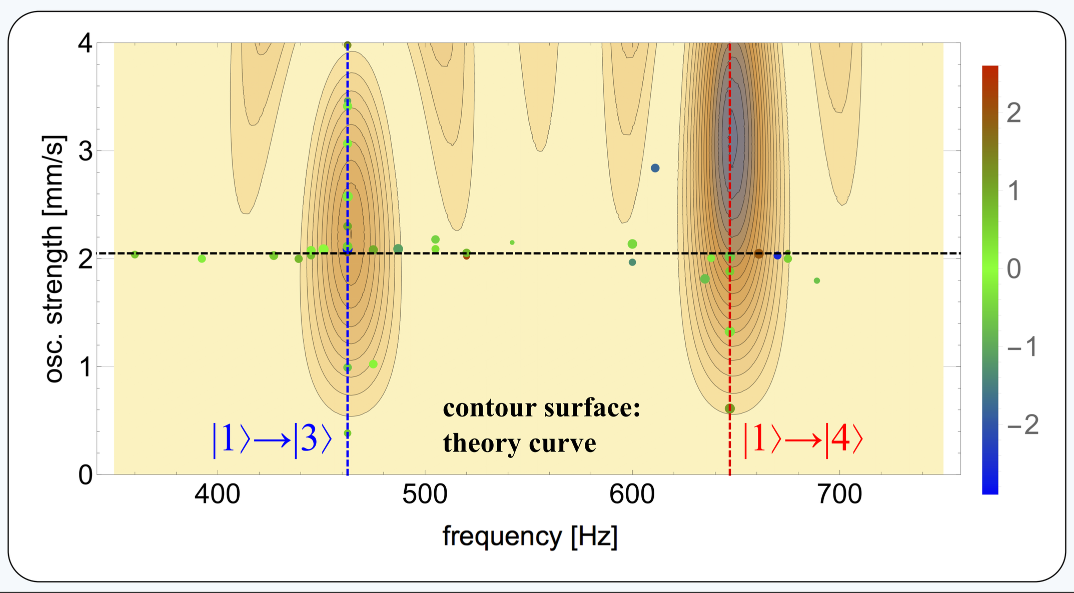
Transmission drop
Rabi curve fitted to data points: $P_{kl} = \left(\frac{\Omega_R}{\sqrt{\Omega_R^2 + \delta\omega^2}}\right)^2 \sin^2\left(\sqrt{\Omega_R^2 + \delta\omega^2}\,t/2\right), \Omega_R = \langle k|\partial_z|l\rangle A_v$

The transmission drops upon resonance. With a three part Rabi-setup, the transitions |1⟩↔|3⟩ and |1⟩↔|4⟩ have been observed at 464.1±(1.2) Hz and 648.8±(1.6) Hz [5].

The curve shows a data subset corresponding to a cut through the contour plot at an oscillation strength of ~2.05 mm s^{-1}.

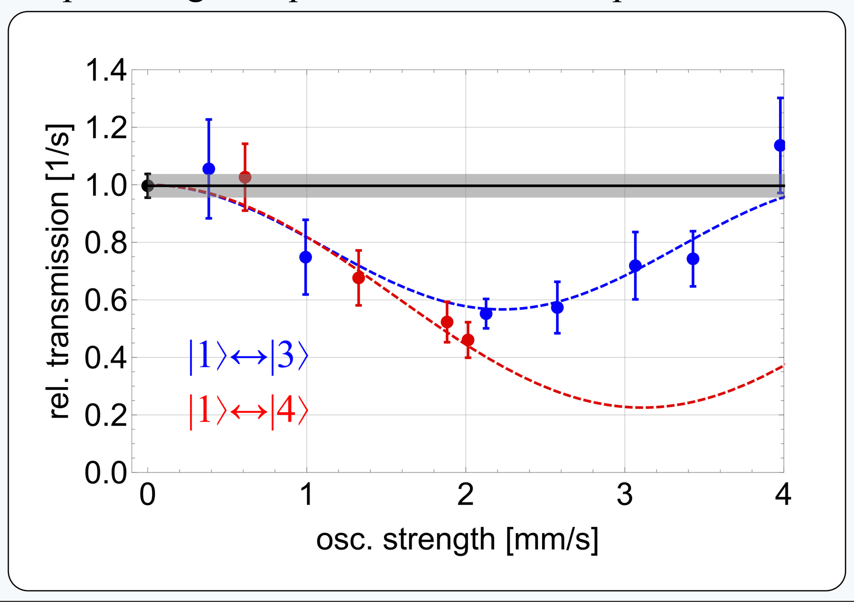


Contour plot
The fitted curve shown with all measurements. The colours of the measurement points show the standard deviation to the fitted curve, their size the statistical significance.



State revival

Additionally the oscillation amplitude can be modified. A minimum of transition is found for a $\pi/2$ pulse and the transmission is restored for a π pulse. Again equidistant binned datapoints are shown.



Acknowledgements

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For inquiring minds...

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