qBounce: Ramsey gravity resonance spectroscopy explained

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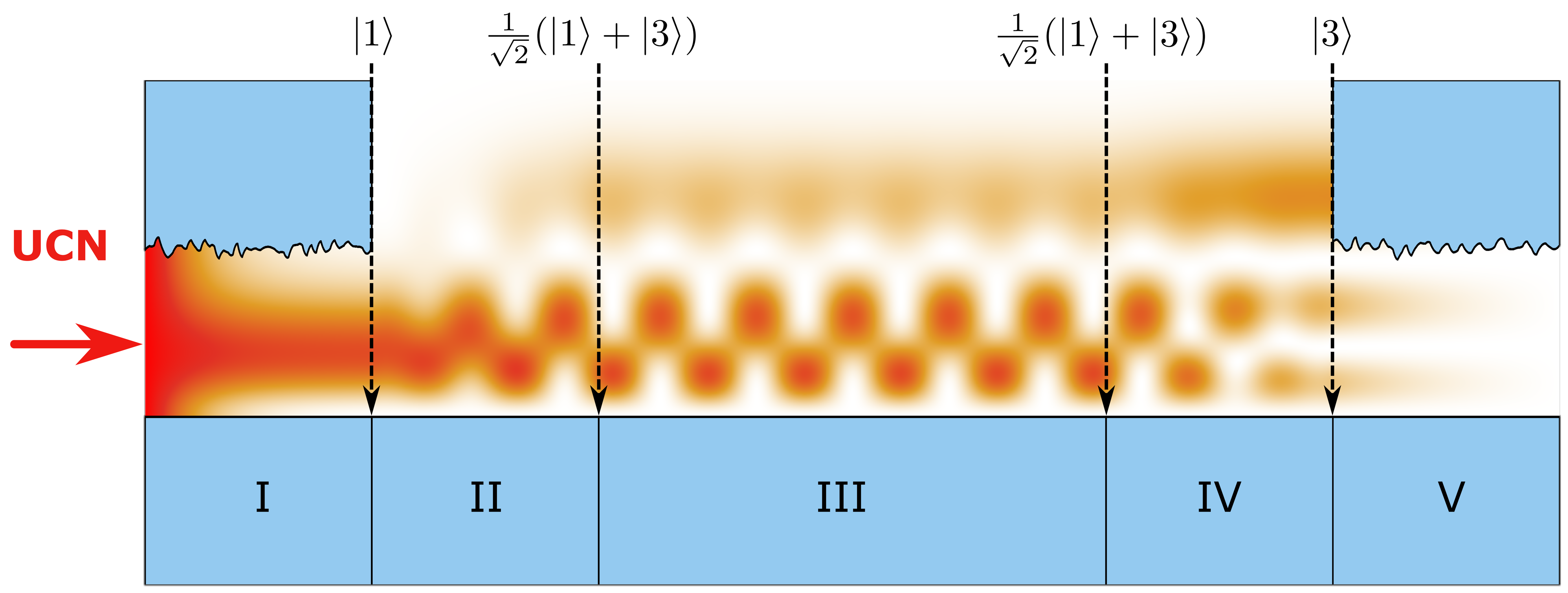
Abstract

The ***q*Bounce** experiment investigates gravity at small distances. This is done using high precision frequency based spectroscopic methods. **Ultracold neutrons** (**UCN**s) form macroscopic bound states above a flat surface in the gravity potential of the Earth, connecting the quantum mechanical neutron wavefunction and gravity. Using this system we developed techniques for **Gravity Resonance Spectroscopy** (**GRS**) [1,2]. We realized a proof of principle with **Ramsey's method of separated oscillating fields** with gravitationally bound UCNs [3]. This method can be used to probe any interaction that couples to the neutron and shifts the eigenenergies of the neutron. Previous iterations of the qBounce experiment implemented GRS in a Rabi configuration and set limits on chameleon dark energy, axion-like **dark matter** and symmetron **dark energy** scenarios [4].

The qBounce experiment is located at the UCN source **PF2** at the **Institut Laue-Langevin** (ILL) in Grenoble. After achieving the proof of principle for Ramsey-GRS in 2018 and optimising experimental parameters during the first half of 2019, we are prepared to take data at a projected sensitivity of 5×10^{-16}eV/day.

Schematic Overview, Example $|1\rangle \longrightarrow |3\rangle$



Section I/V, Preparation/Selection: UCNs enter the setup from the left and **only the first states in the gravity potential are transmitted.** Section I is used to prepare the system in the ground state and section V to scatter all excited neutrons out of the system.

Section II/III, Excitations: **Mechanical oscillation** of the neutron wavefunction mirrors perturb the neutrons. In-phase excitation in sections II and IV leads to a transition from the initial to the target state.

Section III, Propagation: The superposition of states from section II **propagates freely** and the relative phase accumulates according to the energy difference between the states. This **phase is sensitive to all pertubations of the gravitational eigenstates** and allows an anlysis of the perturbing potential.

Experimental key facts

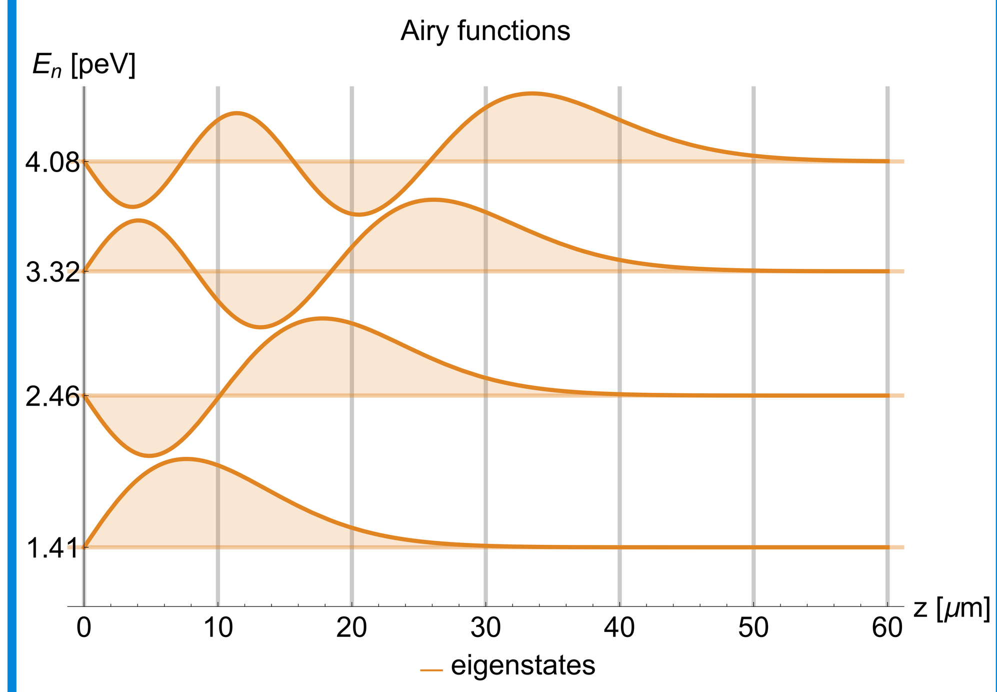
- high vacuum p= 3x10^{-5} mbar
- µ-Metal magnetic shielding with attenuation factor 100
- experiment leveled relative to local gravitational accelleration ≦ 100 nrad
- relative height alignment of mirrors ≦ 500 nm
- detector (neutron counter tube): background (0.63 ± 0.03) ×10^{-3} s-1
- sensitivity:
  - reached: 2x10^{-15} eV (Rabi)
  - short term: 7x10^{-17} eV
  - long term: 5×10^{-21} eV (ideal)

Theory

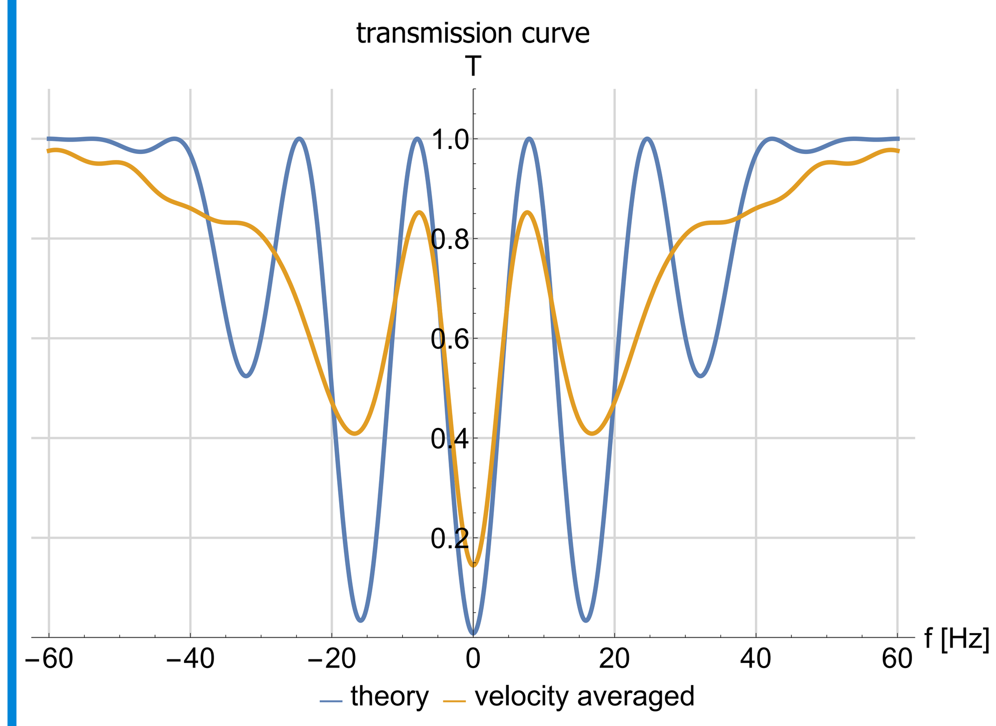
The neutron in the gravity potential is described by the Schrödinger equation with a linear potential

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

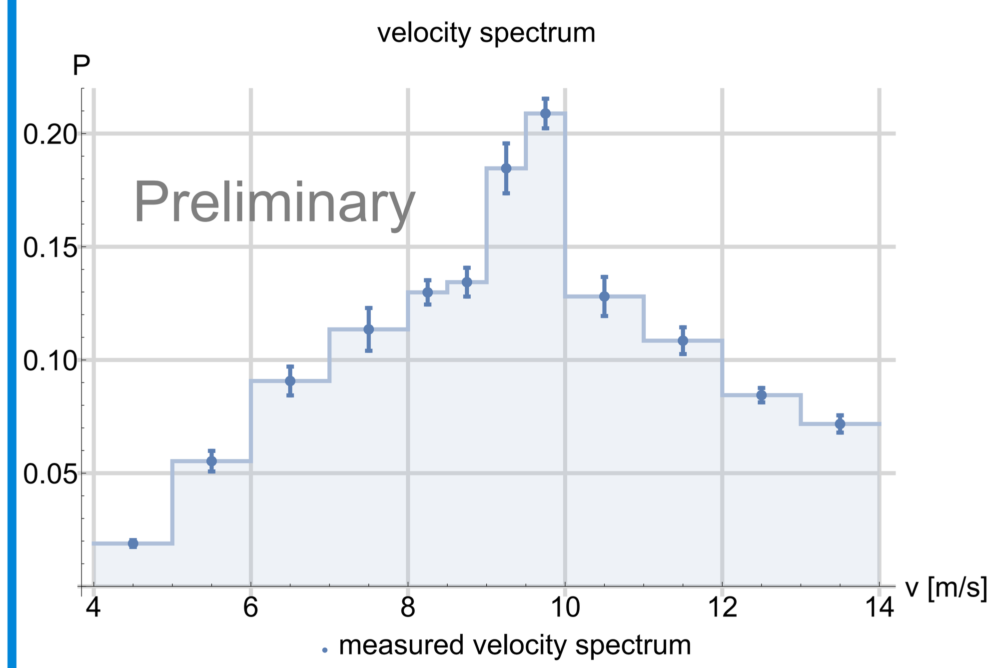
with eigenenergies E_n .
The solutions to this equation are the so called Airy functions.

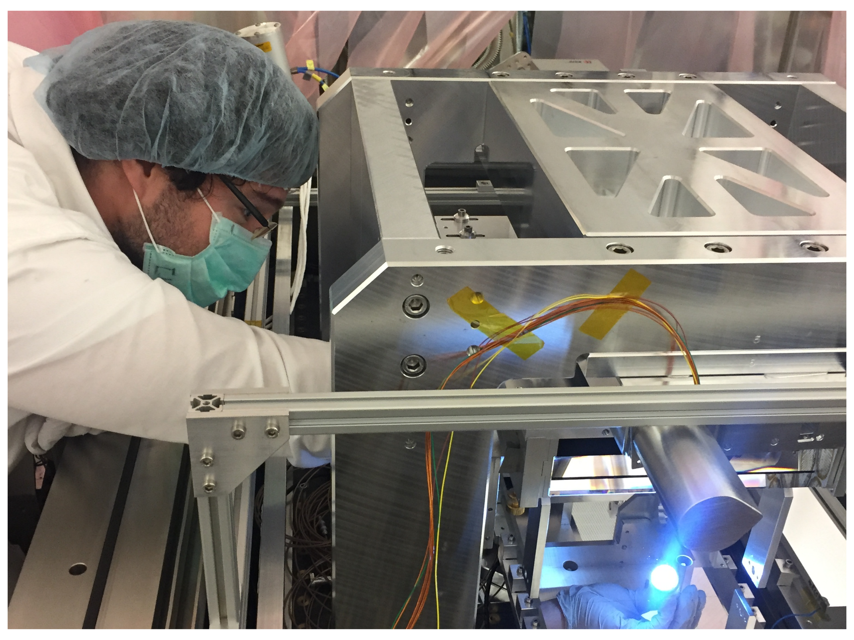


Driving transitions leads to a resonance in the transmission curve.



where the velocity spectrum used for the average was measured in 2019.





[1] Jenke et al., Nature Physics 7, 468-472 (2011)
[2] Jenke et al., Phys. Rev. Lett. 112, 151105 (2014)
[3] Sedmik et al., arXiv:1908.09723[phys.ins-det]
[4] Cronenberg et al., Nature Physics 14, 1022–1026 (2018)

Acknowledements

$\int dk\,\Pi$ Doktoratskolleg Particles and Interactions

FWF Der Wissenschaftsfonds. I529-N20, I531-N20, I862-N20 and P26781-N20

ANR Agence Nationale de la Recherche ANR-2011-ISO4-007-02

DFG Priority Programme (SPP) 1491