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Precision Gravitational Spectroscopy with Ultracold Neutrons and short-range forces: the GRANIT project

(with an introduction about the gravitational quantum spectroscopy in general)
Gravitational quantum spectroscopy with neutrons

Gravitational quantum spectroscopy with antihydrogen (hydrogen) atoms

Ultracold systems: quantum gravitational states: 10 nK, ultracold antihydrogen: 100 μK, ultracold neutrons: 1 mK


Equivalence: gravity and acceleration

Gravitational and whispering-gallery quantum states of neutrons

Essential features:
- The mirror is a uniform potential barrier, with no internal structure,
- The particles are reflected from the mirror elastically,
- Ultracold neutrons (UCNs) are the first particles, which provided measurements of such quantum states;
- Ultracold (anti)atoms is the second candidate particle.
Problem: attractive van der Waals/Casimir-Polder potential.

Solution: Quantum reflection is the limit of lowest energies (gravitational quantum states!!!) provides nearly total reflection of an atom from a mirror.

The quantum reflection of atoms has been demonstrated experimentally.

G. Dufour et al, Quantum reflection of antihydrogen from the Casimir potential above matter slabs, Phys. Rev. A 87, 2013

We have also found materials/conditions, which provide much higher reflectivity - to be published.
Gravity / Acceleration

An illustration for quantum motion of a particle above a mirror in a gravitational field and that in an accelerated frame. The heights of the ball correspond to most probable heights of a neutron in 5th quantum state.

\[ E_n \approx \sqrt{\left(\frac{9 \cdot m_n}{8}\right) \cdot \left(\pi \cdot h \cdot g \cdot \left(\frac{n}{1} - \frac{1}{4}\right)\right)^2} \]
An “artistic” illustration for quantum motion of a particle built of normal matter (left) and antimatter (right) in a gravitational field.

Gravitational and inertial masses of the antiparticle.

Gravitational properties of antimatter have never been measured directly.

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- Observation times are defined by quantum reflection (up to a few seconds)
- Statistics is defined by the phase-space density and the resolution
- Compact design
- Dramatic increase of observation times in microgravity environment

Observation times are defined by the time of flight in the gravitational field (up to a few seconds)
Statistics is defined by the phase-space density and the resolution

- Large sizes
- Increase of observation times in microgravity environment

1. Gravitational quantum states of particles in a gravitational field in the ultimate limit of particle fountains in a gravitational field;
2. The logics of development of interferometric experiments with ultracold neutrons of the previous decades: from fountains to gravitational states;
3. BUT theoretical predication of the large probability of quantum reflections has to be demonstrated experimentally.
Fundamental short-range forces and neutrons

Short-range forces

Phenomenologically:
- Spin-independent,
- Spin-dependent.

Origin:
- Extra light bosons,
- Extra spatial dimensions,
- Dark matter,
- Axion-like particles etc

Neutrons
- Electric neutrality,
- Availability of high fluxes of neutrons with wavelengths comparable to the spatial scale of extra interactions to probe,
- High probability of elastic interaction with matter.
All measurements with neutrons related to the topic of this talk are performed at the Institut Max von Laue - Paul Langevin (ILL), Grenoble, France. All measurements involve ILL scientists (co-authors of relevant publications) and also all measurements use various ILL facilities (GRANIT, PF1B, PF2, D17 etc).
Measurements using UCNs in the EDM apparatus at PSI (Villigen, Switzerland) [S. Afach et al, Phys. Let. B 745 (2015) 58].

Red line (H) shows the new constrain derived from this experiment. Solid line (I) indicates an achievable constraint that could be obtained with a modified installation. A slightly better (then H) constraint was recently measured with polarized $^3$He in M. Guigue et al, Phys. Rev. D 92 (2015) 114001.

Figure 2: Overview of current limits on the product of scalar and pseudoscalar coupling constants $g_S g_P$ as function of the interaction range $\lambda$ of a short range spin-dependent force at 95% confidence level. On the top, the corresponding mass range of the mediating particle, i.e. axion or axion-like particle, is shown. The shaded region is excluded by different experiments. Solid line limits were obtained using cold or ultracold neutrons. Dashed line limits were obtained using $^3$He, $^{125}$Xe, or $^{131}$Xe precession experiments. A [24]; B [25], assuming an attractive interaction; C [26]; D [6]; E [23]; F [20]; G [21]; and H (red) this work. The line I (dotted) depicts the achievable limit by a simple modification of our apparatus (see text).
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More measurements to be done at ILL within the next a few years
Neutron gravitational states.

- Several independent groups (Tokyo, QBounce, GRANIT);
- Building a dedicated facility at ILL for experiments with gravitational quantum states of neutrons in the long-storage mode (GRANIT);
- Neutron results for short-range forces are not yet competitive to results of short-range gravity and Casimir experiments but they are rapidly improving (remember that one should improve by 5-6 orders of magnitude; however, no major systematic effects associated with neutrons have been identified);
- Significant worldwide effort to increase available densities of UCNs.
Transitions between gravitational quantum states

Flow-through mode; limited observation time

Transitions could be excited, for instance:
- By periodically varying magnetic field gradient;
- By periodically varying local gravitational field;
- By oscillating mechanically the mirror.


\[
\delta E_{\text{min}} \approx 10^{-18} \text{eV} \\
\frac{\delta E_{\text{min}}}{E_2 - E_1} \approx 10^{-6}
\]

Probability of transition:

\[
E_i - E_j = \hbar \cdot w_{ij}
\]

\[
\nu_{21} \approx 256 \text{Hz}
\]

Perturbation frequency, Hz

Storage mode: ultimate observation time and energy resolution
Gravitational quantum states in a storage mode

Mirrors are similar to those in the gravitational wave detectors

FIG. 1: The GRANIT instrument at Level C of ILL, Grenoble.

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Gravitational quantum states in a storage mode

Precision characterization of the resulting neutron beam

Large inter-plane distances due to intercalated graphite technology

FIG. 1: The GRANIT instrument at Level C of the INUIT.
The first He-4 UCN source providing UCNs for a "user" experiment (record brightness, small volume)
The simplest configuration of the GRANIT spectrometer in the flow-through mode is similar to the first observation of gravitational quantum states;

- Neighbouring quantum states have never been clearly resolved experimentally;
- This is needed for 1) measuring much more precisely the parameters of quantum states, 2) for providing contrast in experiments with resonance transitions between gravitational quantum states.
First result are promising! 1) the absorber is more efficient by an order of magnitude, 2) UCN flux is sufficient, 3) backgrounds are acceptable.
FIG. 17: The optical elements on the granit table: traction mirrors assembly and the transport mirror on two separate adjustable supports. Their adjustment be done with 3 + 3 micrometric screws. To adjust and the orientation of the surface of the transport a great accuracy, we use 3 piezo-electric elements between the absorber and the transport mirror adjustable as well using 3 piezo-electric elements. The system driven from the control computer with a Labview.

One set of preliminary data

- UCN rate vs. absorber height
  - Valve opened
  - Valve closed (background)
B10 converters

\[ n + ^{10}\text{B} \rightarrow ^7\text{Li} + \alpha, \quad \text{BR} = 6.3\% \]
\[ E_{^7\text{Li}} = 1014 \text{ keV} \quad E_\alpha = 1775 \text{ keV} \]

\[ n + ^{10}\text{B} \rightarrow ^7\text{Li}^* + \alpha \rightarrow ^7\text{Li} + \alpha + \gamma, \quad \text{BR} = 93.7\% \]
\[ E_{^7\text{Li}} = 841 \text{ keV} \quad E_\alpha = 1471 \text{ keV} \quad E_\gamma = 478 \text{ keV} \]

The conversion layer must be
- thick enough to absorb UCNs
- thin enough to allow \( \alpha/\text{Li} \) to escape

Thin layer deposition of B10

Process developed at LPSC using plasma PVD
- 200 nm B layers
- intermediate layer: Ni (~20 nm)
- surface layer: 15-20 nm Ti
The role of Ti and Ni layers

The Ti layer reduces the reflection of slow UCNs, if thin enough;
The Ni layer reflects faster UCNs passing through the B10 layer.

The efficiency
20 nm entrance Ti layer; 20 nm back Ni layer;
account for energy losses in the layer(s);
a few 100 keV detection threshold; 200nm $^{10}$B 84% to 88% efficiency, almost independent of UCN velocity.
Position-sensitive UCN detectors of high resolution

UCN Boron pixels: pixelized detector using commercial CCD sensors: Windowless CCD; Ti-B-Ni layer on top of CCD; Hamamatsu P11071-1106N; 2048x64 pixels 14x14 µm; reconstructed barycenter of alpha clusters

Estimated resolution: ~1µm

Test with α-particles

Energy measurement can be used to improve the spacial resolution for neutrons

Test with UCNs

Test with cold neutrons at PF1B

The spatial resolution for neutrons is better than 3 µm as expected

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UCNBox detector
8 CCD (20cm active region), vertical position and tilt adjustable, dedicated electronics
Better precision and reliability for experiments with neutron whispering gallery; record sensitivity; good chances for major improvements
Figure 2 | A sketch of the effective potential in the cylindrical reference system. The potential step at $z = 0$ is equal to the mirror optical potential $U_0$. The potential slope at $z \neq 0$ is governed by the centrifugal acceleration $a_{centr} = v^2 / R$. The wavefunctions of the two lowest quantum states ($n = 1, 2$) are shown inside the bounding triangle potential at the height corresponding to their energies. The dashed lines illustrate tunnelling of neutrons through the bounding triangle potential.
First observation in 2010 (experiment versus theory) with a Si concave mirror.

Figure 4 | Long-living centrifugal quantum states. a. The scattering probability as a function of neutron wavelength $\lambda$ (Å; vertical axis) and deviation angle $\varphi$ (°; horizontal axis). Neutrons enter through the entrance edge of the mirror. The geometrical angular size of the mirror is 30.5°. The inclined solid lines show the signal shape for the classical Garland trajectories. The dashed horizontal line illustrates a characteristic wavelength cutoff $\lambda_c$. b. Theoretical simulation of the data in accordance with refs 9–11. Some of the difference between these two pictures is probably due to the thin oxide layer on the mirror surface.
Neutron Whispering Gallery: methods

Neutrons tunneling through the mirror

Neutrons passing to the exit of the mirror

Experiment

Theory

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Better precision and reliability for experiments with neutron whispering gallery; record sensitivity; good chances for major improvements.
New experiment with a MgF2 concave mirror

**Improvements:**
- **No Si-oxide layer** on the mirror surface (as in the preceding experiment), thus better defined surface potential and smaller systematics;
- **Lower impurities** on the surface, and thus smaller systematics;
- **Suppression of parasitic transitions** between whispering-gallery states due to the more uniform surface potential;
- **Optimization** of the neutron beam shaping and resolutions, thus higher statistics and lower systematic effects;
- **Better control** of the false effects due to the major experience gained with Si mirrors;
- **Higher critical velocity** of the mirror material, thus the access to shorter distances also higher statistics.
New experiment with a MgF2 concave mirror

Raw data
New experiment with a MgF2 concave mirror

Examples of the data/calcualtions

Analysis of the data is in progress
New experiment with a MgF2 concave mirror

Examples of the data/calculation

Analysis of the data is in progress
Conclusion

- The method of quantum bouncing is gaining ground, attention and support. It is powerful, can be “easy” implemented;

- Neutron (neutron-related) constraints for fundamental short-range interactions are improving in a broad distance range due to efforts of different groups using different methods;

- All these activities are efficient in terms of results/resources;

- These tendencies will stay for the observable future.
after Conclusion

Gravitational states of $\bar{H}(H)$ atoms on the $He$ surface in at fall

$$\tau_{H,\bar{H}}^{gr.1} = \frac{\hbar}{2gbm_{n,H,\bar{H}}} = 1.35 \text{ s}$$

$$t_{0}^{gr.} = \frac{\hbar}{\varepsilon_{0}^{gr.}} = \frac{3}{\sqrt{g^2m_{n,H,\bar{H}}}} = 0.46 \text{ ms}$$

$$\Delta \varepsilon^{gr.} = \frac{t_{0}^{gr.}}{\tau_{H,\bar{H}}} = 3.4 \cdot 10^{-4}$$

$$\frac{\Delta g}{g} \sim 10^{-6}$$

$$\tau_{H,\bar{H}}^{\Delta gr.} = \frac{\hbar}{\Delta g b m_{n,H,\bar{H}}} = 1.35 \cdot 10^6 \text{ s}$$

$$t_{0}^{\Delta gr.} = t_{0}^{gr.} \cdot 4.6 \text{ s}$$

$$\delta_{GBAR}^{st.} \frac{t_{0}^{\Delta gr.}}{\tau_{H,\bar{H}}} \sim 0.03 \cdot \frac{4.6}{1.36 \cdot 10^6} \sim 10^{-7}$$

$$\sim 10^{-7} \cdot 10^{-6} \sim 10^{-13}$$