Quantum interference measurement of the free fall of anti-hydrogen

Joachim Guyomard,
Pierre Cladé & Serge Reynaud
Introduction - GBAR

The GBAR Experiment

- Measurement of gravity interaction of matter on anti-matter, test of the equivalence principle
- Measurement of the free fall time of antihydrogen atoms
- Atom-by-atom detection
- Objective of precision on $\bar{g}$ of the order of $10^{-2}$ with 1000 atoms

[1] P. Blumer Presentation of GBAR at Moriond conference, 2023
Introduction - Classical GBAR; Free Fall chamber

• Ultra cold $\bar{H}^+$ in ground state of an ion trap
• Photodetachment of excess positron by laser pulse
• Freefall until annihilation on Micomega plates
• Objective of **precision on $\bar{g}$ of the order of $10^{-2}$** with 1000 atoms

Today we know $\bar{g} \in [0.46 \, g; \, 1.04 \, g]$\[^{[2]}\]

\[^{[2]}\] E. K. Anderson et al. Observation of the effect of gravity on the motion of antimatter *Nature*, 2023
Introduction - Quantum Reflection

Theoretical Modelisation

- Bounce on the Casimir Polder potential
- We aim for a high reflection probability
- Easier to achieve with fewer bounces
- Reflection due to high variation of the potential near the surface

In the GBAR experiment we hope to drop the $\tilde{H}$ from $h \propto 10 \mu$m

[3] G. Dufour et al. Quantum reflection of antihydrogen from the Casimir potential above matter slabs *PRA*, 2013
• New measurement method, based on interferences
• Quantum bounce on the attractive Casimir-Polder potential
• Atom-by-atom detection
• Objective of precision on $\tilde{g}/g$ of the order of $10^{-5}$ with 1000 atoms$^{[4]}$

[4] P-P. Crépin et al. Quantum interference test of the equivalence principle on antihydrogen PRA, 2019
We want to solve the eigen-value equation:

\[-\frac{\hbar^2}{2m} \frac{d^2 \psi(z)}{dz^2} + V(z)\psi(z) = E\psi(z)\]

with:

\[V(z) = \begin{cases} 
mgz & \text{is } z > 0 \\
+\infty & \text{else}
\end{cases}\]

- Solved by the Airy function:

\[\psi_n(z) = \frac{\theta(z)}{\sqrt{l_g Ai'(-\lambda_n) Ai \left( \frac{z}{l_g} - \lambda_n \right)}}\]

- Where \(l_g := \left( \frac{\hbar^2}{2m^2g} \right)^{\frac{1}{3}} \approx 5.871 \mu m\) & \(\lambda_n\) are the zeros of the Airy function

- Energy scale: \(\epsilon_g = mg l_g \approx 0.6 \text{ peV} \approx 145\text{Hz}\)
• Random draw of N point in the simulated current with $g_0 = 9.81$
• Simulation of the current for different values of $g$
• Maximum Likelihood estimator; $\hat{g}$; over all the simulations
• Standard deviation of $\hat{g}$ after $M$ repetitions gives the measurement

We have $\bar{g}/g \propto 1e^{-5}$
Toward fewer bounce
The fewer the bounces, the simpler the interference pattern.

Possible to test the interferometer with a Hydrogen atom beam.

A two wave interference regime, between one bounce and zero bounce.
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Result - Focalisation of the wavepacket

Study of the one bounce regime

After only one bounce the wavepacket refocalise
This focal point is not well defined in space
We can use this to create interferences inside the bounce

Considering the mirror as a lens we can determine the focal time as
\[ t_f = \frac{t_i^2}{t_i - \frac{v_i}{2g}} \]
Where \( t_i \) and \( v_i \) are the impact time and velocity
The quantum evolution shows explicitly the interferences created at the focal spot.
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Result - Quantum evolution of the Wavepacket

- Cut at the focal time
- Simple interference pattern
- Maximal contrast
- Can be predicted by the stationary phase method over the action
Take Home Message: With about 100 atoms we can achieve a relative precision of the $10^{-5}$ order and have a much simpler interference pattern while having shorten the experimentation time.
• We proposed a new kind of atomic interferometer
• It can be applied beyond the scope of the GBAR experiment
• The GRASIAN experiment aims to test the quantum bounce of Hydrogen
• We hope to apply this method to exotic atoms with a very short lifespan atoms or a very little sample
• We are currently working on the full model with loss and photodetachment taken into account