The Weak Equivalence Principle with antimatter: the AEgIS experiment at CERN

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on behalf of the AEgIS collaboration
- **Universality of free fall** (UFF) established by Galileo and Newton
  
  \[ m_i = m_g \]

  **Weak equivalence principle (WEP)**

<table>
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<tr>
<th>electric field:</th>
<th>gravitational field:</th>
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<tbody>
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<td>( F = q \cdot E )</td>
<td>( F = m \cdot G )</td>
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- **Unique behavior:**

- **Einstein Equivalence Principle:**
  - WEP
  - Local Lorentz Invariance (LLI)
  - Local Position Invariance (LPI)
Test of the EEP

- EEP is the “heart and soul” of **General Relativity (GR)**:
  - EEP valid → gravity is governed by a “metric theory of gravity”


- EEP extensively tested experimentally:

  **Isotropy of atomic energy levels:**  \( \delta = |c^{-2} - 1| > 10^{-23} \)

  **Gravitational red shift:**  \( \frac{\Delta \nu}{\nu} = (1 + \alpha) \frac{\Delta U}{c^2} > 10^{-6} \)

  **Torsion balance:**  \( \eta = \frac{a_1 - a_2}{(a_1 + a_2)/2} > 10^{-13} \)

Some arguments would suggest the WEP holds for antimatter.

Strong theoretical arguments only apply to the idea of antigravity:
- Morrison (1958), Schiff (1958), Good (1961), etc...
- none of them necessarily requires $m_{i}^{\text{antimatter}} = m_{g}^{\text{matter}}$

On the experimental side:

- neutrinos detected from Supernova 1987A
- Shapiro delay of relativistic particles not a test for the EEP
  - G. T. Gillies, Class. Quantum Grav. 29 (2012)
- $p$-$\bar{p}$ cyclotron frequency comparisons: $\frac{\omega_c - \omega_{\bar{c}}}{\omega_c} < 9 \times 10^{-11}$
  - G. Gabrielse et al., PRL 82 (3198) (1999)
- Model dependent, CPT assumption, absolute potentials, …
- and others…but none of them is conclusive
Our attempts for a quantum theory of gravity typically result into new interactions which violate the WEP (ex. KK theory).

Some open questions (like dark matter and baryogenesis) could benefit from a direct measurement.

Because it's possible and no direct measurements are available.

Previous attempts:

- **1967**: Fairbank and Witteborn tried to use positrons. 
  
- **1989**: PS-200 experiment at CERN tried to use (4 K) antiprotons.
  
- Both unsuccessful because of stray E and B fields.

- **2013**: ALPHA experiment at CERN set limit on $m_g/m_i$ for $\bar{H}$.
  - $m_g/m_i > 110$ excluded at 95% CL.
• At CERN antimatter studies are possible thanks to the **Antiproton Decelerator (AD)**

• 26 GeV/c p from PS used to produced $\bar{p}$

• AD slows down $\bar{p}$ to $\sim 100$ MeV/c in a 100 s cycle

• Approximately $3 \times 10^7 \bar{p}$ delivered each cycle
The AEgIS experiment

- **Goal**: direct measurement of the Earth’s local gravitational acceleration $g$ on $\overline{H}$ with a final precision of some percent

- **How**: by measuring the vertical displacement of the shadow image produced by an $\overline{H}$ beam through a Moiré deflectometer
AEgIS collaboration

21 Institutes and 80 people

Stefan Meyer Institute
University of Genova
Institute of Nuclear Research of the Russian Academy of Science
University of Bergen
University of Lyon 1
INFN sections of: Genova, Milano, Padova, Pavia, Trento

CERN
University of Milano
Max-Planck Institute Heidelberg
University of Bern
University of Oslo

Czech Technical University
University of Padova
Politecnico di Milano
University of Brescia
University of Paris Sud

ETH
University of Pavia
University College London
Heidelberg University
University of Trento
The AEgIS apparatus

Moiré

$\bar{H}$

$H$ production trap

$\bar{\rho}$ catching trap

$\bar{H}$ production trap

$1 \ T$

$5 \ T$

$e^+$

$\bar{\rho}$
Antihydrogen production strategy

- Rydberg $\bar{H}^*$ atoms produced via *charge exchange*

\[
Ps^* + \bar{p} \rightarrow H^* + e^-
\]

- $\sigma \propto n_{Ps}^4 \rightarrow n_{Ps} \sim 20 - 30$

- $n_{\bar{H}}$ determined by $n_{Ps}$

- Temperature of $\bar{H}$ given by the temperature of $\bar{p}$

- Rydberg $\bar{H}$: strong dipole moment $\rightarrow$ **Stark acceleration**
Antiproton capture and cooling

- Electrons (~$10^8$) loaded in the trap

- Thin Al foil (degrader) used to select low energy antiprotons

- $\bar{p}$ caught and cooled (electron cooling)
  - ~7 K reached currently

- some $10^5 \bar{p}$ catch per spill
- **Positronium** (Ps) is an exotic atom composed by an e\(^-\) and a e\(^+\)
- **para-Ps** (125 ps) and **ortho-Ps** (142 ns)
- Ps produced via electron capture of e\(^+\) within a nanoporous silica target

**AEgIS status**: Positrons

- Lifetime ~ 100s e\(^+\) source accumulator
- Transfer line

- **\(^{22}\)Na source**
- **Solid neon moderator**

\[ e^+ \xrightarrow{\text{capture}} \text{SiO}_2 \xrightarrow{\text{Si}} \text{e}^- + \text{e}^+ \]

\[ \text{para-Ps} (125 \text{ ps}) \text{ and } \text{ortho-Ps} (142 \text{ ns}) \]

up to \(8 \times 10^8\) e\(^+\)

bunches of \(\sim 10^7\) e\(^+\) transfer \(\epsilon > 0.8\)
Positronium excitation

Two stages excitation:

- **UV (205 nm):** \( n = 1 \rightarrow 3 \)
- **IR (1650-1700 nm):** \( n = 3 \rightarrow 25 - 35 \)

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S. Mariazzi et al., *NIM B* 269 (2011) 1527
Gravity module

which must be smaller than the diffraction angle $\frac{\lambda}{d} = k_{dB}$, where $k_{dB}$ is the de Broglie wavelength of the matter wave. All of these limitations can be alleviated by increasing the grating period relative to the de Broglie wavelength. At the point where $d^2 = L/C^2$, diffraction no longer occurs.

The resulting device is the so-called Moiré deflectometer, in which diffraction on the gratings is replaced by a (classical) shadow pattern of those particles that converge onto the third grating. Interestingly, the gross characteristics of the interferometer are retained, in particular, the vertical displacement of the interference pattern according to Eq. (2). A three-grating Moiré deflectometer has been used to measure the local gravitational acceleration to a relative precision of $2 \times 10^{-10}$ with a beam of argon atoms traveling at an average velocity of 750 m s$^{-1}$.

In departing from the three-grating deflectometer, we intend to replace the third grating by a position-sensitive silicon strip detector (see Fig. 4). Thereby the overall transmission of the apparatus is increased by the inverse of the grid's open fraction (roughly a factor of three).

The value of $g$ is extracted from the primary observables (time of flight $T$ and vertical displacement of the fringe pattern $d_x$) in the following way, as illustrated by Monte-Carlo simulations performed by us: First, the ensemble of all annihilation events on the detector is plotted as a function of $T$, as shown in Fig. 5 (a). These events are binned in symmetric classes of $T^2$, one of which is shown shaded in dark blue in the figure. Secondly, the vertical displacement $d_x$ of the fringe pattern is extracted for each of the count classes, as illustrated in Fig. 5 (b). Thirdly, the vertical displacement for all count classes is plotted against the mean time of flight in the class. A quadratic fit to that graph, as shown in Fig. 5 (c), will then yield $g$. In these simulations, a grating period of 80 µm was used, and a finite detector resolution of 10 µm was taken into account.

Our simulations have shown that in order to perform a measurement of $g$ to 1% relative precision, about $10^5$ H atoms at a temperature of 100 mK will be required. This could be achieved within about 2–3 weeks of data taking, assuming the AD beam is shared among four experiments. The grids and detector must be kept precisely aligned for the entire data taking period, which can be achieved by an auxiliary laser beam.
• AEGIS experiment is taking data (\(\bar{H}\) production expected in 2016)

• Small-scale test of the Moiré deflectometer with \(\bar{p}\) was performed
Results: (mini) Moiré test with antiprotons

- 146 antiprotons recorded

\[ \Delta y = 9.8 \pm 0.9 \text{(stat)} \pm 6.4 \text{(syst)} \ \mu m \]

- \[ F = 530 \pm 50 \text{ aN (stat.)} \pm 350 \text{ aN (syst.)} \]

- consistent with a \( B \sim 7.4 \ G \)

B \( \sim 10 \ G \) measured at the Moiré position
Conclusions and future plans

Goal

• AEgIS aims at probing the WEP on antimatter
  • No direct measurement so far

Results

• AEgIS is taking data
• The working principle tested using antiprotons
  • Stray B field → no gravity measurement possible on $\bar{p}$

Future plans

• $\bar{H}$ production expected to be achieved later this year
• First gravity measurements planned for the next years
• Longer term plans also include H-$\bar{H}$ spectroscopy