Testing the Weak Equivalence Principle with Antimatter

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AEGIS: Antimatter Experiment: Gravity, Interferometry, Spectroscopy

• Main goal: Measurement of $g$ with a few percent* precision on antihydrogen
  * (initially)

• Proposed in 1997 by Tom Phillips

• Requirements / challenges:
  – Production of a bunched cold beam of antihydrogen (100 mK)
  – Measurement of vertical beam deflection (10 μm drop over 1 m)
Outline

- Motivation / Prospects for anti-gravity
- AEGIS principle and setup
- Current status
- Conclusions and outlook
Motivation

- Weak equivalence principle (WEP):

  “In a uniform gravitational field all objects fall with the same acceleration, regardless of their composition.”

- WEP extremely well tested with matter, but never with antimatter

- Electric charge of subatomic particles

\[
\bar{m}_g = \bar{m}_i
\]
Motivation

• Gravity is the only force **not** described by a quantum field theory

• QFT formulations of gravity open the way for
  – Non-Newtonian gravity
  – WEP violation
  – Fifth forces etc.

• Since 2002 copious amount of neutral antiatoms have become available

Antimatter

- 1928 Paul Dirac predicts antimatter
- 1932 Carl Anderson discovers the positron in cosmic rays
- 1955 Owen Chamberlain et al. publish “Observation of antiprotons”
- 1956 discovery of antineutrons
- 2002 first production of cold antihydrogen atoms
- 2011 first storage of antiatoms for 1000 s
When matter and antimatter collide particles annihilate.

CPT theorem by W. Pauli:

“Every canonical quantum field theory is invariant under simultaneous inversion of charge, parity, and time.”

Antimatter perfect mirror image of matter
Antihydrogen

hydrogen

proton

electron

antihydrogen

antiproton

positron
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Antiproton Decelerator at CERN

- $10^7 \bar{p}$ produced every $\approx 90$ s
- Deceleration from $p = 3.5$ GeV/c to 100 MeV/c
- Fast extraction (200-ns bunches)
AD experiments

1. Antiproton production
2. Injection at 3.5 GeV/c
3. Deceleration and cooling (3.5–0.1 GeV/c)
4. Extraction (≈2×10⁷ in 200 ns)

Electron cooling
Stochastic cooling

AEGIS
ATRAP
ASACUSA
ALPHA

Schematic overview of the apparatus

Ps transfer line

Antiproton beam

5T

1T
AEGIS overview sketch

- positronium source & accumulator
- AD beamline
- antiproton & positron trapping
- antihydrogen production
- position-sensitive detector
- Moire deflectometer
Antiproton capture and cooling

- Energy reduced by 50-µm degrader foil

- Trapping sequence:
  1. Trap is prepared with plasma of $10^8$ cold electrons
  2. Small fraction of antiprotons with $E < 9$ keV is reflected
  3. Axial potential on entrance side is raised to trap $\bar{p}$
  4. Antiprotons are sympathetically cooled by electrons

- Trap cooled to 100 mK by a dilution refrigerator
- sympathetic cooling with laser cooled negative ions
Positronium production

- Positrons from a $^{22}$Na source
- Formation of positronium in nano-porous silica based materials

Ortho Ps  
$\tau = 140\text{ ns}$

Para PS  
$\tau = 125\text{ ps}$

- Measurements ongoing at Trento and Munich (NEPOMUC) to optimize Ps conversion targets
  - at 50 K, 9% of positrons converted to Ps

Antihydrogen recombination

- **Charge exchange reaction:**
  \[ \text{Ps}^* + \bar{p} \rightarrow \bar{H}^* + e^- \]

- **Principle demonstrated**
  by ATRAP
  \[ \text{Cs}^* \rightarrow \text{Ps}^* \rightarrow \bar{H}^* \]

- **Advantages:**
  - Large cross-section:
  - Narrow and well-defined \( n \)-state distribution
  - Antiproton temperature determines antihydrogen temperature

\[ \sigma \approx a_0 n^4 \]

Experimental sequence

- Principle sketch (not to scale):

1) Antiproton capture & cooling
2) Positron production
3) Positronium conversion
4) Positronium excitation
5) Antihydrogen recombination
6) Antihydrogen beam formation
7) Gravity measurement
8) Data analysis
Antihydrogen acceleration

- Rydberg antihydrogen accelerated into a beam by inhomogeneous electric field

\[ \vec{F} = -\frac{2}{3} e a_0 n(n - 1) \nabla \vec{E} \]

Gravity measurement

- Forces can be measured with a series of slits
  - Formation of an interference or shadow pattern with two slits
  - Measurement of the vertical deflection $\delta x$ with a third (analysis) slit
- Many slits: interferometer/deflectometer

- Vertical deflection due to gravity: $\delta x \approx -10 \, \mu m$
- Vertical beam extent: $\Delta x \approx 5.8 \, cm$

(antihydrogen beam at 100 mK, accelerated to 500 m s$^{-1}$, $L \approx 0.5 \, m$)
Data analysis

• Record vertical position for each event as a function of TOF/velocity:

\[ v_{\text{beam}} = 600, 400, 300, 250 \text{ m s}^{-1} \]

\[ \delta x = -gT^2 = -g(L/v)^2 \]


• Summing up the peaks:

Measurement of \( g \) to 1%:

– \( \approx 10^5 \) \( \Hbar \) atoms at 100 mK
– about 2 weeks of beam time
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AEGIS construction 2010–2012

September 2011

December 2012
Magnets and traps

• 5 T magnet (capture) and 1 T magnet (H recombination) installed and commissioned

• All traps completed & commissioned

• Beam times May & Dec. 2012:
  – Successful $\bar{p}$ stacking (4 shots, $4 \times 10^5 \bar{p}$)
  – Storage of cooled $\bar{p}$ ($\tau = 570$ s)

About $1.3 \times 10^5$ p caught at 9kV per AD bunch $\sim 3 \times 10^7$
Moiré $\bar{\text{H}}$ detector

- Requirement: Detect $\bar{\text{H}}$ annihilations with resolution $\Delta t \approx 1 \, \mu s$, $\Delta x \approx 10 \, \mu m$

- Currently favored design:

  - Time of flight from 1D Si strip
  - High spatial resolution provided by emulsion
  - 2D Si tracker correlates emulsion tracks with timed events
Moiré $\bar{H}$ detector

- Nuclear emulsions:
  - 90 $\mu$m thick gels on glass substrate (0.5...1 mm thick)
  - Based on technology developed for OPERA, modified for vacuum operation and tested at low temp
  - Off-line analysis by automatic 3D scanning

Intrinsic resolution 58 nm
Vertex resolution $\approx$ 1.4...2.3 $\mu$m
Moiré deflectometer

- Deflectometer test setup

- Stability of gratings measured with laser: 30 nm over 1 h
- Prototype deflectometer commissioned with metastable Ar atoms
  → first gravity measurement
Moiré deflectometer

- December 2012:
  Deflectometry measurement with $\bar{\rho}$ in “mini moiré” setup
  - $d = 40 \, \mu m$, $L = 25 \, mm$
  - $100 \, keV \bar{\rho}$, 7 h exposure
  - Reference measurement with laser light in Talbot-Lau regime

Result:
- Phase shift: $10.0 \, \mu m \pm 0.9 \, \mu m \text{(Stat.)}$
  $\pm 6.3 \, \mu m \text{ (Sys.)}$
- Force: $F = 540 \pm 50 \pm 340 \, aN$, corresponds to magnetic field $\approx 8 \, G$

[Aghion et al., submitted 2013]
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Conclusions & outlook

• the weak equivalence principle has never been tested for antimatter
• depending on the chosen model, effect could be nil or dramatic
• the AEGIS experiment intends to measure $g$ of antihydrogen to few percent precision
• construction and commissioning of AEGIS apparatus largely completed
• next milestones:
  – 2013 / first half 2014: Commissioning of all remaining components;
  – from second half 2014: First antimatter gravity experiment