Measuring the gravitational acceleration of antimatter with antihydrogen

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University of Bern
Outline

1. Why study the gravitational behaviour of antimatter?

2. Background: from the first anti-atoms to “cold” antihydrogen.

3. Trapped antihydrogen & the first direct antimatter gravity measurement.

4. (Near) future measurements with an antihydrogen beam.
Acknowledgements

Colleagues from AEgIS and ALPHA.
Material from many sources (too many to list!).
1. Why study the gravitational behaviour of antimatter?
Discovery of antimatter (1932) \(\rightarrow\) raised question of its reaction to a gravitational field.

Big Bang model (1948). Number of variants proposed:

1) Matter and antimatter symmetric universe
   - mechanism for their separation,
   - antigravity \(\rightarrow\) repulsion between matter & antimatter.

2) Asymmetry of matter & antimatter.

Discovery of CP-violation (1964) \(\rightarrow\) 1) forgotten about...
Standard Model of Big-Bang Cosmology

Inflationary universe dominated by Dark Matter & Dark Energy

Lambda-CDM model:
• Structure of the CMB
• Abundance of H,D,He,Li
• Accelerating expansion of the universe
Problem with Lambda-CDM Model

Excellent parametrisation of current data, but requires 2 ingredients which are undetected and/or not understood.

Dark Energy:
• Required to explain accelerating expansion of space. But what is it?!
• Cosmological constant: why this value?
• Vacuum energy: $10^{120}$ smaller than expected from QFT.

Dark Matter:
• Required to explain gravitational effects observed in large scale structures.
• But still escapes direct detection...
The Dirac-Milne Universe: Renewed interest as an alternative to Lambda-CDM

Matter - antimatter symmetric universe. Antimatter has a negative active gravitational mass.

- Type Ia Supernova distances ✓
- Abundance of light elements ✓
- CMB acoustic scale ✓

What happened to the antimatter?
What is dark energy?
What is dark matter?

A. Benoit-Lévy, G. Chardin
A&A 537 A78 (2012)
What do we currently know about the gravitational behaviour of antimatter?

**Direct evidence**

**Indirect evidence**

- Quark fraction,
- Torsion balance experiments,
- Cyclotron frequencies of p/pbar,
- CP-violation in neutral Kaons.
Indirect evidence: Quark fraction

Large fraction of the inertial mass of a proton or antiproton comes from its binding energy.

Assuming quark mass is 1% of the overall mass, then even if $g/g\bar{g} = -1$, antiproton would not "fall-up".

Maximum observable effect at the 1% level.
Indirect evidence:

Torsion balance experiments

T = k \left( \frac{m_{iA}}{m_{gA}} - \frac{m_{iB}}{m_{gB}} \right)
Indirect evidence: Torsion balance experiments

- $|\Delta a/a| < 2.5 \times 10^{-12}$
- Binding Energy fraction for Be = 0.995 Binding Energy fraction for Cu

Difference in gravitational attraction for ordinary mass compared to nuclear binding energy < $5 \times 10^{-10}$.
Indirect evidence: Torsion balance experiments

Difference in gravitational attraction for ordinary mass to nuclear binding energy $< 5 \times 10^{-10}$.

Direct measurement.

But what does this say about antimatter?!

- Suppose some fraction of proton mass attributable to the masses of (virtual) anti-quarks.
- Different elements (may) have different virtual antimatter proportions.
- However, coupling strength of gravity to virtual particles is not known (Vacuum Catastrophe).

Can’t say much about the gravity of antimatter here.
Indirect evidence:
Cyclotron frequencies

Test of the weak equivalence principle from particle-antiparticle frequencies.

\[ f = \frac{q_p B}{2\pi m_{i,p}} \]

\[ f = \frac{q_{\bar{p}} B}{2\pi m_{i,\bar{p}}} \]
Indirect evidence: Cyclotron frequencies


\[ f = \frac{q_p B}{2\pi m_{i,p}} \]

Local time of proton sped up by \( 1 + \frac{G M}{R c^2} \)

\[ f = \frac{q_{\bar{p}} B}{2\pi m_{i,\bar{p}}} \]

Local time of antiproton sped up by \( 1 + \frac{(g/g) G M}{R c^2} \)
Indirect evidence: Cyclotron frequencies

- Observed by us (matter!) people, cyclotron frequency of antiproton will be different to an amount proportional to $(1 - \frac{\bar{g}}{g})GM/Rc^2$.

- Antiproton and proton cyclotron frequency measured to be the same to part in $10^{10}$.

- Bound on antigravity depends on choice of $R$ and $M$, i.e. choice of the absolute gravitational potential.

- Assume gravitational potential from local supercluster

\[ \left| 1 - \frac{g}{\bar{g}} \right| < 5 \times 10^{-4} \]
Indirect evidence: Kaon Oscillations

• Uses same gravitational redshift effect arguments.

• Look for annual / monthly modulations of CP-violating observables, e.g.

\[ |\eta_{+-}|^2 \approx |\epsilon|^2 + \frac{(\delta m_{\text{eff}})^2}{8(\Delta m)^2} \]

\[ \delta m_{\text{eff}} = M_{K^0}(g - \bar{g})_1 \frac{U}{c^2} \gamma e^{-r/r_1} \]

• S. G. Karshenboim, preprint 0811.1009v1 [gr-qc] (2008):

\[ \left| \left( \frac{m_g}{m_i} \right)_{K^0} - \left( \frac{m_g}{m_i} \right)_{\bar{K}^0} \right| \leq 8 \times 10^{-13} \text{ at CL=90\%} \]

• But, must assume an absolute gravitational potential...

• Neutral kaons are a mixture of matter and antimatter.
Indirect evidence:
Kaon Oscillations

North-Holland

CP violation.
A matter of (anti)gravity?

G. Chardin
DAPNIA/SPP, Centre d’Etudes de Saclay, F-91191 Gif-sur-Yvette, France

and

J.-M. Rax
PPPL, Princeton University, J. Forrestal Campus, Princeton, NJ, USA

Observed CP-violation consistent with $\bar{g} = -g$ i.e. antigravity!
Motivation: 
Personal view...

• Indirect evidence: $\Delta g/g$ between $10^{-13}$ and 100%
  $\rightarrow$ Worth doing a direct measurement!

• Experimentally possible (as I’ll show in a moment).

• Techniques developed to do the experiment, are also applicable for spectroscopy experiments (CPT tests).

• New field of research combining particle, atomic, plasma & laser physics to test fundamental physics.
Direct Gravitational Tests of Antimatter: 
Free-fall Measurements of Neutral Antimatter
Antimatter gravity experiments at Cern: Growing competition

First experimental limits

ALPHA I (April 2013): Free-fall style measurement with trapped antihydrogen.

Current & future experiments

AEGIS (2011-): Free-fall style measurement with an antihydrogen beam.

Gbar (2012-): Free-fall style measurement with laser ionised Hbar+.

ALPHA II (2012-): Improved measurement by laser cooling trapped Hbar.
Why antihydrogen?

Free-fall experiments with charged antimatter (e+, p̅) failed:

\[ F_{\text{gravity}} \ll F_{\text{electromagnetic}} \]

Requires:

\[ e^+ \quad E < 10^{-12} \text{ V/m} \]
\[ p̅ \quad E < 10^{-7} \text{ V/m} \]

Not possible: due to patch effect.

Antihydrogen: simplest neutral anti-atom.
Gravity experiments require ultra-cold $\bar{H}$ (sub-Kelvin).

<table>
<thead>
<tr>
<th>$\bar{H}/\bar{p}$ kinetic energy (temp.)</th>
<th>GeV ($10^{12}$ K)</th>
<th>PS210 (CERN, 1997): First $\bar{H}$ anti-atoms.</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>eV ($10^3$ K)</td>
<td>ATHENA (CERN, 2003): First cold $\bar{H}$ production.</td>
</tr>
<tr>
<td></td>
<td>$\mu$ eV (sub-K)</td>
<td>ALPHA (CERN, 2010): Trapped $\bar{H}$.</td>
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</table>

14 orders of magnitude drop in energy in 13 years (1997-2010)!
2. Background: From the first anti-atoms to “cold” antihydrogen.
First antihydrogen atoms

First atoms of antihydrogen created by PS210 at CERN’s Low Energy Antiproton Ring (LEAR) in 1995.

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

Ref: http://ikpe1101.ikp.kfa-juelich.de/ps210/

But, 2 GeV/c (10^{13} K) not useful for precision studies.
Why do we need cold antihydrogen?

Spectroscopy requires “long” interrogation times.

Require an atom trap, which are typically very shallow (few K).

AEgIS will measure gravitation attraction by creating an antihydrogen beam.

Require antihydrogen atoms < 0.1 K.

Need to produce “cold” (<1K) antihydrogen!
Energy scales

Antihydrogen Experiments

GeV/c $\overline{p}$

μeV/c $\overline{\text{H}}$

LHC

TeV/c LHC p

eV/c p

eV

$10^{15}$ K

$10^{12}$ K

$10^{9}$ K

$10^{3}$ K

(sub-K)
Energy scales

Antihydrogen Experiments

- TeV ($10^{15}$ K)
- GeV ($10^{12}$ K)
- MeV ($10^9$ K)
- eV ($10^3$ K)
- μeV (sub-K)

LHC
Cern's Antiproton Decelerator (AD): The world's only source of cold antiprotons
Antiproton production

\[ p + p \rightarrow p + p + \bar{p} + p \]

Air cooled Iridium target

\[ P \rightarrow 3.5 \text{ GeV/c} \]

\[ 26 \text{ GeV/c} p \]
Antiproton Decelerator (AD)

1. 26 GeV/c p on Iridium
   \[ pp \rightarrow pp + \bar{p}p \]

2. Inject 3.5 GeV/c \( \bar{p} \)

3. Deceleration & cooling to 100 MeV/c

4. Extract 100 MeV/c \( \bar{p} \)
Antiproton Decelerator (AD)
Antihydrogen experiments at CERN's Antiproton Decelerator (AD)
Trapping antiprotons

Axial confinement: static electric fields.
Radial confinement: Lorentz force in solenoidal B-field.
Catching antiprotons

Passed through 100 μm foil: $\sim 10^5$ below 4 keV. Catch antiprotons by switching on high voltage.
What about positrons?

Potassium-40 in bananas: 1 e+ every 75 minutes

Sodium-22 isotope (made with p accelerator): \( \sim 10^6 \) e+ every second.

\[ ^{22}\text{Na} \rightarrow ^{22}\text{Ne} + e^+ + \nu_e + \gamma \]
Positron accumulation

$^{22}\text{Na}$

$\sim 0.2 \text{ MeV}$

Neon moderator

$\sim 25 \text{ meV}$

$\sim 300\text{M }e^+ \text{ every few minutes.}$

Producing antihydrogen

Confine antiprotons and positrons in the same region of space with a “Nested Penning Trap”

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

ATHENA (2002):
First production of cold $\bar{\mathcal{H}}$

- CsI crystals
- Si strip detector
- Penning trap
First production of cold $\bar{H}$

3. Trapped antihydrogen & the first direct antimatter gravity measurement.
Why trap antihydrogen?

- Penning traps only confine charged particles. Neutral $\bar{\text{H}}$ annihilates $< 1 \mu s$ after creation.
- Spectroscopy $\rightarrow$ keep the $\bar{\text{H}}$ for “some time” ($> 1$ ms).
- Solution: trap $\bar{\text{H}}$ in a magnetic atom trap.

Goal of ALPHA & ATRAP collaborations at Cern’s AD since 2006.

- Later realised that the release of antihydrogen from the neutral trap could be used for gravity measurement!
Why is this difficult?

- Magnetic atom trap: uses a magnetic field gradient to trap “low-field-seeking” atoms.

- (Anti-) atom is trapped if $H$ kinetic energy is less than the magnetic well depth, i.e. $k_B T < \mu \Delta B$

  \[ \text{For } \Delta B = 1 \text{T} \rightarrow T < 0.7 \text{ K!} \]

- $\bar{p}$ extracted at 5 MeV, require 0.1 meV $\bar{H}$: 10 orders magnitude reduction in temperature!
## ALPHA collaboration (~40 authors)

<table>
<thead>
<tr>
<th>Institution</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aarhus University, DK</td>
<td>G.B. Andresen, P.D. Bowe, J.S. Hangst</td>
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<td>University of Liverpool, UK</td>
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<td>University of Tokyo, JP</td>
<td>R.S. Hayano, D.M. Silveria</td>
</tr>
<tr>
<td>York University, CA</td>
<td>S. Menary</td>
</tr>
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</table>
2 mirror coils + octupole $\rightarrow$ 3D magnetic minimum.
ALPHA:
Producing, Trapping & Detecting Antihydrogen
Typical trapping experiment

1. Cool e+ by means of evaporative cooling.
2. Autoresonantly inject antiprotons into positrons.
3. Remove charged particles.
4. Wait 173ms (later 100+ s) → turn off neutral atom trap.

5. Identify trapped antihydrogen!
Identifying antihydrogen atoms

Reconstruct annihilation vertex with 3 layer double sided silicon strip detector.

Magnetic atom trap material → too much multiple scattering to identify location of the e⁺e⁻ annihilation.

University of Liverpool
Identifying trapped antihydrogen

- If all charged particles are removed: annihilation after turning off the neutral trap → trapped antihydrogen.

- Complication: magnetic gradients of the atom trap can also trap uncombined antiprotons (“mirror-trapped antiprotons.”)

Is it trapped $\tilde{H}$ or mirror-trapped $\tilde{p}$?
Identifying mirror-trapped antiprotons

potential (V)

magnetic field (T)

axial position (m)

right bias
left bias

time (ms)

axial position (m)
November 2010: Trapped antihydrogen!

38 antihydrogen atoms trapped! Background $1.4\pm1.4$

Recent progress

June 2011: Confinement of antihydrogen for 1,000 seconds (ALPHA, Nature Physics 7, 558–564).


April 2013: Description and first application of a new technique to measure the gravitational mass of antihydrogen (ALPHA, Nature Communications 4, 1785).
Gravity measurement with trapped antihydrogen: Simulation of annihilation locations

\[ F = \frac{M_{\text{gravitational}}}{M_{\text{inertial}}} \]

Simulation: \( F = 100 \)

Data: 434 annihilations

Average position of $y$-annihilations: Event data vs. simulation for $F=1, 60 \& 150$

Reverse cumulative average: average of the $y$ positions of all annihilations that occur at time $t$ or later.

Red circles: $y$-annihilation positions.

Green triangles: $x$-annihilation positions.

Black line: average $y$ of simulation.

Grey band: 90% confidence region.

Gravity measurement with trapped antihydrogen: ALPHA result

Exclude with 95% confidence:

\[ F > 110 \text{ (normal gravity), } & \]

\[ F < -65 \text{ (antigravity).} \]

First free-fall style, model independent measurements of antimatter gravity.

Prospects for the more interesting \( F = +/- 1 \) regime?

Gravity measurement with trapped antihydrogen: Future prospects

4. Antimatter gravity measurements with an antihydrogen beam
Antimatter gravity experiments at CERN: Expanding programme

New antiproton decelerator: Extra Low ENergy Antiproton (ELENA) ring.

Slows AD antiprotons to 100 keV + electrostatic extraction.
Antimatter gravity experiments at CERN: Expanding programme

New antiproton decelerator: Extra Low ENergy Antiproton (ELENA) ring.

Slows AD antiprotons to 100 keV + electrostatic extraction.


ELENA project ensures antiproton physics for the next ~20 years.
# AEgIS collaboration (~70 authors)

<table>
<thead>
<tr>
<th>Institution</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>CERN, Switzerland</td>
<td>University of Oslo and University of Bergen, Norway</td>
</tr>
<tr>
<td>INFN Genova, Italy</td>
<td>Czech Technical University, Prague, Czech Republic</td>
</tr>
<tr>
<td>INFN Bologna, Italy</td>
<td>INFN Padova-Trento, Italy</td>
</tr>
<tr>
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<td>ETH Zurich, Switzerland</td>
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<tr>
<td>Max-Planck-Institut für Kernphysik Heidelberg, Germany</td>
<td>Laboratoire Aimé Cotton, Orsay, France</td>
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<tr>
<td>INFN, Università degli Studi and Politecnico Milano, Italy</td>
<td>University College, London, United Kingdom</td>
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<tr>
<td>INFN Pavia-Brescia, Italy</td>
<td>Stefan Meyer Institut, Vienna, Austria</td>
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<tr>
<td>INR Moscow, Russia</td>
<td>University of Bern, Switzerland</td>
</tr>
<tr>
<td>Université Claude Bernard, Lyon, France</td>
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</tbody>
</table>
Principle of the experiment

Antihydrogen beam (uncollimated)

moiré deflectometer

Free-fall detector (position, time)

Earth

$\bar{H}$ counts vs. vertical co-ordinate

0

1

2

3

y
The AEgIS apparatus
The AEgIS apparatus

- flight region
- $\bar{H}$ production traps
- catching traps
Antihydrogen production & beam creation

1. Load & cool antiprotons
2. Trap & then “fire” 500M e+ onto convertor
3. Laser excite Ps → Ps*
4. Ps* + p → H* + e-
5. Accelerate H
Current status

- Catching traps
- Positron accumulator & transfer line
- Ps production target, fiber for laser excitation, & antihydrogen production traps
- Antihydrogen detector
Experimental challenges

Experimental approaches:

1. Produce cold antihydrogen (resistive, evaporative, laser cooling).
2. Produce more antihydrogen (Ps production, enhance Ps overlap).
   and/or
3. Minimise the number of antihydrogen atoms that need to be detected on the free-fall detector for a $\Delta g/g = 1\%$ measurement.

For all Hbar to reach free-fall detector:

Solid angle $\rightarrow v_{radial} \leq 100\text{mK}$
How much flux(*) do we need?

$\Delta g/g$ dependency on vertex position resolution

velocity = 600 m/s

Free-fall detector (position, time)

Antihydrogen beam

moiré deflectometer

$\text{pitch } p = 40 \mu\text{m}$

$\text{Hbar}$

100 mK

resolution

1 $\mu$m

3 $\mu$m

5 $\mu$m

7 $\mu$m

10 $\mu$m

13 $\mu$m

15 $\mu$m

Relative intensity

$2\pi/p \cdot \Delta x = \text{phase shift}$

$gT^2$
How much flux(*) do we need?

$\Delta g/g$ dependancy on vertex position resolution

Higher resolution $\rightarrow$ fewer Hbar atoms required for the measurement.
What tracking detector technology has the highest position and angular resolution?

Nuclear emulsion based detectors (*)

emulsion layer (44 microns)

base layer (200 microns)

emulsion layer (44 microns)

SEM cross sectional view of standard film by FUJI film

AgBr crystal suspended in a gelatine matrix.

(*) Integrating detector, no timing information.
Emulsion detectors: Intrinsic resolution

10 GeV/c pion beam

56nm intrinsic resolution

100 microns

number of grains

residuals / nm

James Storey
Emulsion detectors: Current state-of-the-art

Long history of use in particle physics e.g. discovery of the antiproton.

100cm$^2$ emulsion film $\rightarrow$ $10^{14}$ channels of AgBr crystal detectors, each with a detection efficiency of 16% for a MIP.

Automated scanning (Univ. Nagoya) $\rightarrow$ 20 cm$^2$/hour (European Scanning System at Bern)

Graphical Processor Unit (GPU) based track reconstruction algorithms (Bern)

AEgIS raw image data $\rightarrow$ 1 TB/hour
Emulsion based free-fall detector: How will it work?

H annihilation produces (in $2\pi$): 2 pions + 1 proton or 1 pion + 2 protons.
Emulsion based free-fall detector: How will it work?

Grain density $\rightarrow dE/dx \rightarrow$ proton / pion separation.
Measurements with antiprotons during the 2012 AD run: Experimental setup

emulsion films (yellow)
50 microns

5000 events / cm\(^2\)
Topographic readout of the emulsion by optical scan
Antiproton annihilation in a bare emulsion

150 µm x 120 µm x 50 µm
Prof. Gösta Ekspong (91)

1st observed annihilation star (Bevatron, 1955)
Reconstructed tracks and annihilation vertices

Angular distribution of reconstructed tracks

Reconstructed tracks

Reconstructed vertices

emulsion films (yellow)

track perpendicular to emulsion surface = 0°
Antiproton annihilation vertex resolution

Vertex resolution perpendicular to emulsion surface

-300 -260 -220 -180 -140 -100
z-coordinate of reconstructed vertex (μm)

Emulsion layer
Bare emulsion sample
Stainless steel sample

Number of entries / 4μm

0 50 100 150 200 250 300 350

r.m.s. resolution ≈ 1μm
on the vertical position of
the annihilation vertex

Impact parameter (μm)

Bare emulsion sample
Stainless steel sample

vertex resolution

0 0.1 0.2
a.u.

0 1 2 3 4 5
Hybrid detector concept: **Nuclear Emulsion** + **Scintillating-fiber/Silicon Tracker (NEST)**

- Silicon strip detector (50 μm) + transparent window
- ~ position, TOF
- Nuclear Emulsion position
- Scintillating fiber/Silicon Tracker charged pion tracks, TOF
Alignment between moiré gratings and emulsion detector

Absolute reference can be “stamped” directly on emulsion surface.
Simulated performance

Annihilation position resolution = 1-2 μm
Efficiency (require 2 tracks traversing emulsion) = 50%

With a 2μm position resolution how many antihydrogen atoms do we need for Δg/g = 1%?

~600 fully reconstructed and time tagged Hbar annihilations

Implication: can afford to relax other (challenging) requirements e.g. Hbar temperature.
Comparison: AEgIS vs. ALPHA

**AEgIS**: $500 \times 100\text{mK}$ atoms $\rightarrow F=0.01$

Systematics: $F=0.01$

Timescale: 2-3 years.

**ALPHA**: $500 \times 10\text{mK}$ atoms $\rightarrow F=1$

Systematics: $F>110$

Timescale: develop laser cooling of e+ & Hbar $\rightarrow$ 3-5 years (also required for spectroscopy). **Solve systematic problems $\rightarrow ?$ years.**
AEgIS: Outlook

2014  Antihydrogen production & beam creation.

2015  First attempts at free-fall measurement.
Summary

- No direct evidence against antigravity. Indirect limits are the subject of much debate.

- Era of fundamental physics measurements with antihydrogen has begun. First, model independent, free-fall style measurement performed by ALPHA.

- Growing competition between experiments at the CERN AD to measure the free-fall of antihydrogen. AEgIS experiment is on schedule for a free-fall measurement in 2015.
Thanks for listening!

Contact james.storey@cern.ch if you would like to visit AEgIS!