The GBAR antimatter gravity experiment

**Equivalence Principle**
“The trajectory of a point mass in a gravitational field depends only on its initial position and velocity, and is independent of its composition and structure.”

\[ \vec{P} = m_G \vec{g} \]
\[ \vec{F} = m_I \vec{a} \]

Apollo 15 – 1971

Galileo – 1602
Why study gravitation and antimatter?

- It has never been measured!
- No quantum theory of gravity
  - Big Bang model → same quantity of matter and antimatter, but Antimatter not seen!
  - energy content: matter (4%), dark matter(22%), dark energy (74%) of unknown nature
  - antigravity or modified gravity?

Attempts to construct cosmology with matter-antimatter symmetry + mechanism to keep them apart: gravitational repulsion
negative gravitational masses? gravitational dipoles?

Quantum theories (superstrings, SUSY, ...) contain scalar and vector terms on top of tensor → components of repulsive gravity
→ gravity may be more complicated than classically thought.
  → antimatter may behave differently in a gravity field generated by matter (the Earth)
Matter Experiments: best constraint

Torsion balance (Eötvös)

\[
(\Delta a / a)_{\text{Be/Ti}} = (0.3 \pm 1.8) \times 10^{-13}
\]
• Cyclotron frequency of $p$ & $\bar{p}$ in same $B$ field


  \[
  \omega = \frac{qB}{2\pi m} + \frac{\alpha U}{c^2} \quad \left| \omega - \bar{\omega} \right| / \omega = \left(9 \pm 9\right) \times 10^{-11}
  \]

  \[
  \rightarrow \left| g - \bar{g} \right| / g \leq 5 \times 10^{-6}
  \]

• Arrival time of 1 (? : 90 % CL) neutrino and 18 antineutrinos from SN1987a


  \[
  \left| \gamma(\nu_e) - \gamma(\bar{\nu}_e) \right| / \gamma(\bar{\nu}_e) < 10^{-6}
  \]
• **Positrons (e⁺) or Antiprotons (p̅)**
  
  gravity force on e±
  
  ~ force from 1 elementary electric charge at 5 m

• **Antineutrons**
  
  difficult to slow down and keep enough

• **Neutrinos**
  
  wait for next supernova?

• **Positronium (e⁺e⁻)**
  
  Lifetime 142 ns, cooling, ionisation by black body radiation, project by D. Cassidy at UCL

\[
\frac{m_{eg}}{e} = 5.6 \times 10^{-11} \text{ V} / \text{m}
\]
Antimatter Experiments: ALPHA result

**Antihydrogen**

\[ F = \frac{M_G}{M} \]

![Graph showing annihilation vertex during release of trapping field](image)

- **Green dots** — simulated annihilations
- **Red circles** — 434 observed annihilations

Position of annihilation vertex during release of trapping field
Antimatter Experiments: Antihydrogen gravity

$$m_i \ddot{a} = m_g \ddot{g}$$

$$h = v_{z0}^0 t + \frac{1}{2} \frac{m_g}{m_i} g t^2 = v_{z0}^0 \left( \frac{L}{v_h} \right) + \frac{1}{2} \frac{m_g}{m_i} g \left( \frac{L}{v_h} \right)^2$$

<table>
<thead>
<tr>
<th>AEGIS</th>
<th>GBAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\overline{H}$ beam</td>
<td>cooled $\overline{H}^+$ → slow $\overline{H}$</td>
</tr>
<tr>
<td>L</td>
<td>1 m</td>
</tr>
<tr>
<td>h</td>
<td>20 μm</td>
</tr>
<tr>
<td>$v_h$</td>
<td>500 m/s</td>
</tr>
<tr>
<td>$T_H$</td>
<td>100 mK ~ 7 μeV</td>
</tr>
</tbody>
</table>

Goal

$$\frac{\Delta g}{g} \leq 1\%$$
Gravitational Behaviour of Antihydrogen at Rest
- $\overline{H}^+ = \bar{p} \ e^+ e^+$
- Capture $\overline{H}^+$ in trap
- Sympathetic cooling with $\text{Be}^+ \rightarrow 10 \ \mu K$
- Photodetachment of $e^+$
- Time of flight

J.Walz & T. Hänsch,

$$h = 10 \text{ cm} \rightarrow \Delta t = 143 \text{ ms}$$
$$h = 1 \text{ mm} \rightarrow \Delta t = 14 \text{ ms}$$
GBAR principle: \( \overline{H}^+ \) production

Standard production:
\[
\overline{p} + e^+ + e^+ \rightarrow \overline{H}^* + e^+
\]

\( \overline{H}^+ \) Formation

Reaction first demonstrated by G. Gabrielse (2004)

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

\[
\overline{H} + Ps \rightarrow \overline{H}^+ + e^-
\]

\( P. \) Pérez & A. Rosowsky, NIM A 532, 523-532 (2004)

\[
\begin{align*}
10^7 \overline{p} & \quad \rightarrow \quad 10^4 \overline{H} \\
10^{12} Ps /cm^2 & \quad \rightarrow \quad 1 \overline{H}^+
\end{align*}
\]
a possibility to enhance $\bar{H}^+$ production

\[ \bar{p} + Ps(n_{Ps}, l_{Ps}) \rightarrow \bar{H}(n_{H}, l_{H}) + e^- \quad (3\text{-body}) \]

\[ \bar{H}(n_{H}, l_{H}) + Ps(n_{Ps}, l_{Ps}) \rightarrow \bar{H}^+ + e^- \quad (4\text{-body}) \]

P. Comini, P-A. Hervieux and F. Biraben, LEAP 2013
GBAR overall scheme
Antiprotons: CERN AD / ELENA

1. Antiproton Production
2. Injection at 3.5 GeV/c
3. Deceleration and Cooling (3.5 - 0.1 GeV/c)
4. Extraction (3 x 10^7 in <300 ns)

Location for future ELENA installation

100 keV

5 MeV

ELENA
Layout
1 pulse / 110 s
100 keV ā pulse
300 ns (1.3 m)

4π mm mrad

drift tube

- 99 kV

switch

- 1 kV

1 keV (0.2 m)

40π mm mrad
Positron production and storage
e+/Ps demonstrator at Saclay

- Trap
- Switch
- Slow e+
- Pulse stretcher
- e+/e- separator
- Linac
- Target & moderator
- e+ → Ps
- Converter test line
e+/Ps demonstrator at Saclay

- 4.3 MeV / 200 Hz / 2.5 μs / 120 μA
- 3 \times 10^6 slow e^+ / s
- with first W mesh moderator

- Penning trap on beam line (from RIKEN)
- First trapping trials

- Secondary beam line
- \rightarrow moderator developments
- \rightarrow e+/Ps converters

- Ps* laser being prepared at LKB (Paris)
Concrete shielding

X rays

e+/Ps demonstrator at Saclay

e⁻ Linac  Ec = 4.3 MeV  I = 0.14 mA
RIKEN Multi-Ring Trap

- Superconducting Solenoid
- Faraday Cup & Phosphor Screen
- MRT
- B-5T
- W(100)
- CCD
- γ Detector

Position Adjuster for e⁻ Beam (ExB)

e⁻ Beam

e⁺ Beam
$e^+$ trapping

electron plasma for cooling

Potential on axis (V)

-1000 -800 -600 -400 -200 0 200 400

Z position (m)

-0.8 -0.6 -0.4 -0.2 0 0.2 0.4

Magnetic Field $B_z$

e$^+$ pulse

e$^+$ trapped between barriers

Gate closed

Gate open

$H_2^+ + e^+$ plasma

Longitudinal Magnetic Field on axis (T)

0.01 0.1 1 10 100

Trapped positions (arb. unit.)

0 500 1000 1500 2000 2500 3000 3500 4000

Accumulation time (s)

0.01 0.1 1 10

with electron plasma

without electron plasma
Positronium production
Ps formation

1 mm × 1 mm × 2 cm Si with mesoporous SiO$_2$ coating

Test on ETHZ beam line
Transmission @ 5 keV ~ 100%
Ps formation efficiency as for bare SiO$_2$
Same Ps lifetime distribution

P. Crivelli, WAG2013
Ps excitation laser (n=3)

- Doubled YAG 6 W
- Pulsed YAG 236 mJ
- CW Ti:Sa 460 mW
- Ti:Sa Oscillator 4 mJ
- Cs cavity
- Ti:Sa Amplifier
Capture and cooling of $\bar{H}^+$
Cooling challenges

Reaction chamber

Kinetic energy 1 .. 6 keV
Temperature 60 .. 300 eV
700 000 K

Capture + Cooling

Trapped particule
Temperature 3 neV
20 μK

Cold trapped $\overline{H}$

Classical world

Frontiers of Quantum world

NIST D. Wineland
Innsbruck R. Blatt

$L.\ Hilico\ et\ al.,\ Int.\ Journal\ \ Mod.\ Phys:\ Conf.\ Series,\ 30\ (2014)\ 1460269.$
Two cooling steps

**First step**
Capture and sympathetic Doppler cooling by laser cooled Be$^+$ ions in the linear **capture trap** (Paul trap, $r_0 = 3.5$ mm, $\Omega = 13$ MHz)

![Capture trap diagram]

> 10 000 laser cooled Be$^+$ ions
100 neV, $T \sim $ mK

**Second step**
Transfer and ground state cooling of a Be$^+$/H$^+$ ion pair in the **precision trap**

tests with H$_2^+$ / H$^+$ REMPI source
$\bar{H}^+$ cooling simulations

9/1 mass ratio: bad mechanical coupling
9/2 mass ratio: much better mechanical coupling

Idea: try an intermediate ion 9 / 3 / 1

C. B. Zhang, D. Oenberg, B. Roth, M. A. Wilson, and S. Schiller,
L. Hilico et al., IJMPCS 2014

few meV $\bar{H}^+$

1800 Be$^+$
200 HD$^+$
1 $\bar{H}^+$

L. Hilico et al., (2014)
Raman side band cooling

\[ \text{Be}^+ \rightarrow \text{H}^+ \]

197 GHz

\[ 313.13 \text{ nm} \]

\[ \nu_{\text{hfs}} = 1.25 \text{ GHz} \]

\[ F=0, 1, 2, 3 \]

\[ F=1, 2 \]

\[ \Delta \]

\[ 2S_{1/2} \]

\[ 2P_{3/2} \]

\[ \text{Dop}_1 \]

\[ \text{Dop}_2 \]

\[ n=0, 1, 2, 3, 4, 5, 6 \]
Precision trap being prepared at Mainz
Laser table ready for tests with Ca\(^+\)/Be\(^+\), later Sr\(^+\)/Be\(^+\)
$ar{H}$ free fall detection

```
LASER 1.64 μm

1 Be$^+$
1 H$^+$
$\sim$ neV
DETECTION

LASERS 313 nm

CAPTURE & COOLING
$\bar{H}^+ - \text{Be}^+$

LINAC e$^-$ 10 MeV

W TARGET & MODERATOR
e$^+$ 3 eV

BUNCHER e$^+$ 1 keV

TRAP

ELENA (CERN - AD)
$\bar{p}$ 100 keV

DECELERATOR $\bar{p}$ keV

FOCUS

Ps

keV $\bar{H}$

keV H$^+$

keV $\bar{p}$

keV e$^+$

keV e$^-$
```

04 Sept. 2014
P. Pérez - USTC Hefei
**H** free fall detection

**Detection**

<table>
<thead>
<tr>
<th>Detection</th>
<th>Requirement</th>
</tr>
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<tbody>
<tr>
<td>TOF precision</td>
<td>150 μs</td>
</tr>
<tr>
<td>Annihil. vertex precision</td>
<td>2 mm</td>
</tr>
<tr>
<td>Background rejection</td>
<td>event topology</td>
</tr>
</tbody>
</table>

*Figure showing a graph with the axes labeled as $T = 10 \mu K$ and $\Delta E = 1 \mu eV$.*

*Figure showing a detector setup with various labeled components including laser beams, annihilation plate, and antihydrogen cloud.*
MicroMegas detector

Argon Isobutane (95%, 5%)
Pitch of strip ~ 400 microns
X and Y strips give track position directly

Genetic multiplexing of strips
S. Procureur et al, NIM A 729 (2013) 888
Quantum reflection on a step

plane wave incident on a potential step:

\[ \Psi_{in}(z) \propto \exp(-ikz) \] with 

\[ k = \sqrt{2m(E - V)} / \hbar \]

wave function partly transmitted, partly reflected

reflection:

\[ r_{12} = \frac{k_2 - k_1}{k_1 + k_2} \]

transmission:

\[ t_{12} = \frac{2\sqrt{k_1k_2}}{k_1 + k_2} \]

reflection from attractive potential

Reflection probability unchanged when

1 \leftrightarrow 2

\[ |r_{12}|^2 = |r_{21}|^2 \]
The Casimir - Polder force

Electromagnetic (EM) modes are modified when the atom comes close to the detector:

⇒ the EM ground state (vacuum) energy changes
⇒ attractive Casimir-Polder force between atom and detector

---


Casimir 1948: long-range interaction energy between an atom and a perfectly conducting mirror:

\[ V^*(z) = -\frac{3\hbar c}{8\pi z^4} \frac{\alpha(0)}{4\pi \epsilon_0} = -\frac{C_4^{\text{perfect}}}{z^4} \]

For \( \text{H} \) and \( \overline{\text{H}} \), \( C_4^{\text{perfect}} \approx 73.6 \): \( E_h a_0^4 \)

\[ V(35 \text{ nm}) \approx -mg \times 10 \text{ cm} \]
Reflection probability

altitudes are quantized
→ spectroscopy
i.e. improved precision

already demonstrated with ultra cold neutrons at ILL (V. Nesvizhevsky)
Gravitational States of Neutrons

Velocity selector


First simulations \(\rightarrow\) optimise dimensions with experimental constraints

\( h = 50 \, \mu m \)

\( H = 20 \, \text{cm} \), \( R_{\text{detector}} = 20 \, \text{cm} \)

Shaper \( R_{\text{min}} = 1 \, \text{mm} \), \( R_{\text{max}} = 7 \, \text{mm} \)

\( \rightarrow \) need 150 produced \( H^+ \) for \( \Delta g/g = 1\% \)

10 times less than in proposal
15 institutes  ~ 50 researchers

**new collaborators welcome!**

- 2015: start installation
- 2016: ELENA commissioning with p and H⁻
- 2017: first antiprotons for GBAR