Probing Gravity with antimatter

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24^{th} of March 2020

Outline of the presentation

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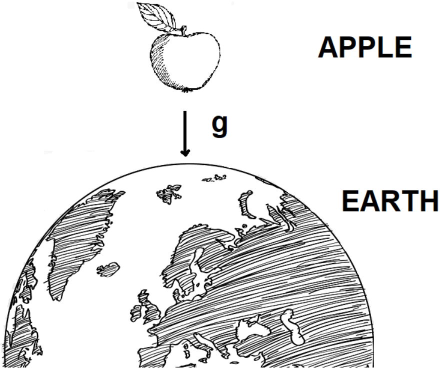
Gravitational field interaction

- Standard model: matter and antimatter (charge conjugated particles).
- Baryon asymmetry problem - Where is antimatter?
- Explanation: the gravitational interaction?



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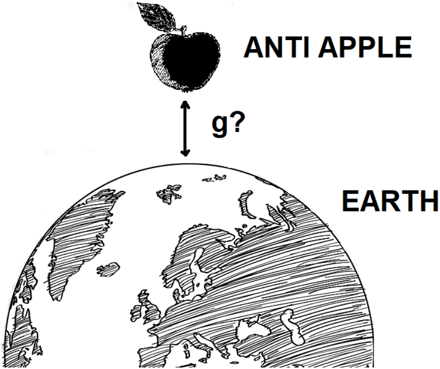


Gravitational field interaction

- CPT invariant Standard Model.
- The Weak Equivalence Principle - the universality at the heart of the General Relativity:
  - Universality of free-fall - all particles (or antiparticles) fall with the same acceleration in a gravitational field (WEPff).
  - Universality of clocks - all dynamical systems which can be viewed as clocks (e.g. (anti)atomic transition frequencies. frequency of (anti)particle motion in the Penning trap) measure the same gravitational time dilation independently of their composition (WEPc).
- More theory about the extensions of the Standard Model can be found in for example: "Testing Fundamental Physics in Antihydrogen Experiments" by M. Charlton, S. Eriksson and G.M. Shore, arXiv:2002.09348v1.

How can we test WEP for antimatter?

WEP for antimatter - a bit of history

- The first experimental idea anyone can get - let the antimatter fall!
  - 1968, William Fairbank - free fall of electrons and positrons - impossible, due to stray field. M. M. Nieto, T.Goldman, Physics Reports Volume 205, Issue 5, July 1991, Pages 221-281.
  - 1990s, PS200 experiment - free fall of antiprotons from LEAR. Closed.
- Supernova 1987A - time of the detection of ν_e and $\bar{\nu_e}$ from the supernova (about 164,000 light years away) set the limit on WEP to 10^{-6}. Sandip Pakvasa, Walter A. Simmons, and Thomas J. Weiler, Phys. Rev. D 39, 1761.
- 1991, measurement by the TRAP collaboration (G. Gabrielse et al.) interpreted by R. J. Hughes and M. H. Holzscheiter, the first WEPc constrain at the level of 5×10^{-4} by measuring the cyclotron frequency of an antiproton in the Penning trap.
- 2013, the ALPHA collaboration, rejected ratios of gravitational to inertial mass of antihydrogen > 75.
- 21st century WEP experiments for antimatter:
  - free fall experiments;
  - clock experiments.

Outline of the presentation

The free fall experiments

- The "easiest" is to make a classical free fall experiment.
- Main issue: for the resolution $\Delta g/g$ the falling particle energy has to be in the mK - μK regime (or lower).
- Neutral systems:
  - Ps - positronium - the bound state of an electron and a positron (para-positronium - 125 ps; ortho-positronium 142 ns lifetime);

    → for example D. Cassidy at UCL. R. Ferragut at Politecnico di Milano.
  - Mu - muonium - the bound state of an antimuon and an electron (2.2 μs lifetime);

    → A.Soter, MAGE experiment (expected 1%), arXiv:1802.01438.
  - $\bar{\mathrm{H}}$ - antihydrogen - an atom made from a positron orbiting around a nucleus composed of one antiproton (stable!);

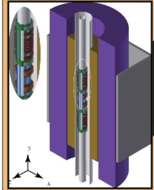
    → AEGIS experiment (expected 1%);
    → ALPHAg experiment (expected 1%);
    → GBAR experiment (expected first stage 1%, later 10^{-5}).

Comparison of antihydrogen experiments (recap)

Plurality of approaches

VERTICAL TRAP
- increase up/down sensitivity (up to 1.3m trapping range)
- much improved field control

Sign measurement planned soon
1% targeted H̄ cooling to ~20 mK and advanced magnetometry

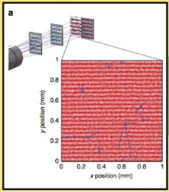


W. A. Bertsche Phil. Trans. R. Soc. A 2018 376 20170265; DOI: 10.1098/rsta.2017.0265. (2018)

ALPHA-G

H̄ BEAM
- Sensitivity to ~10 μm deflection needed
- cold antiproton translates in cold H̄ thanks to CE mechanism

Sign measurement targeted

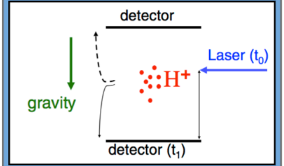


S. Aghion et al. Nature Communications 5 (2014) 4538

AEGIS

H̄+ BEAM
- Cooling below 1 m/s : Sympathetic cooling of H̄+
- opens new horizons

1% measurement targeted



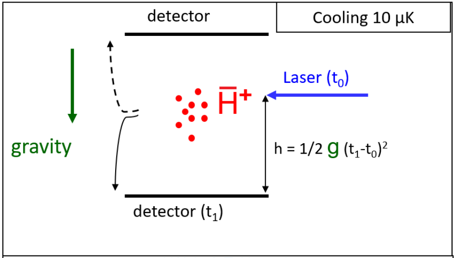
e.g.: The GBAR antimatter gravity experiment
P. Pérez et al., Hyperfine Interactions 233, 21-27 (2015)

GBAR

Slide credit to C. Malbrunot

Gravitational Behaviour of Antihydrogen at Rest

- Goal: **Test the weak equivalence principle for antimatter using antihydrogen atom with at least 1% precision.**
- The principle of the GBAR experiment:
  - antihydrogen $\bar{\mathrm{H}} \leftrightarrow \bar{p} + e^{+}$;
  - antihydrogen ion $\bar{\mathrm{H}}^{+} \leftrightarrow \bar{p} + e^{+} + e^{+}$.



J.Walz & T. Hänsch,
General Relativity and Gravitation, **36** (2004) 561

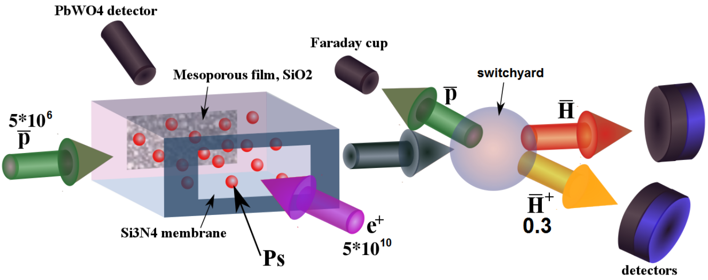
- 1 event gives 37% uncertainty, and 1500 events 1% ($h = 10$ cm $\rightarrow t = 0.14$ s, $\Delta t < 150\ \mu$s, $\Delta s < 100\ \mu$m).
- Further goal: 10^{-5} precision with spectroscopy of the gravitational quantum levels of the $\bar{\mathrm{H}}$ atom (A. Yu. Voronin, P. Froelich, V. V. Nesvizhevsky, Physical Review A 83, 032903 (2011)).

Antihydrogen atom and ion production

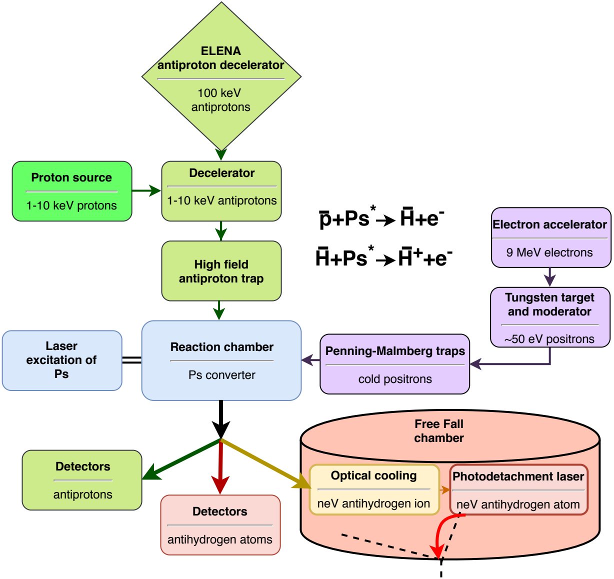
- The first large part of the experiment is to prepare the antihydrogen ion beam (P.Pérez and A. Rosowsky, NIM A 532 (2004) 523):

$$\bar{\mathrm{p}} + \mathrm{Ps}(n_p, l_p, m_p) \to \bar{\mathrm{H}}(n_h, l_h, m_h) + e^-$$

$$\bar{\mathrm{H}}(n_h, l_h, m_h) + \mathrm{Ps}(n_p, l_p, m_p) \to \bar{\mathrm{H}}^+ + e^- .$$

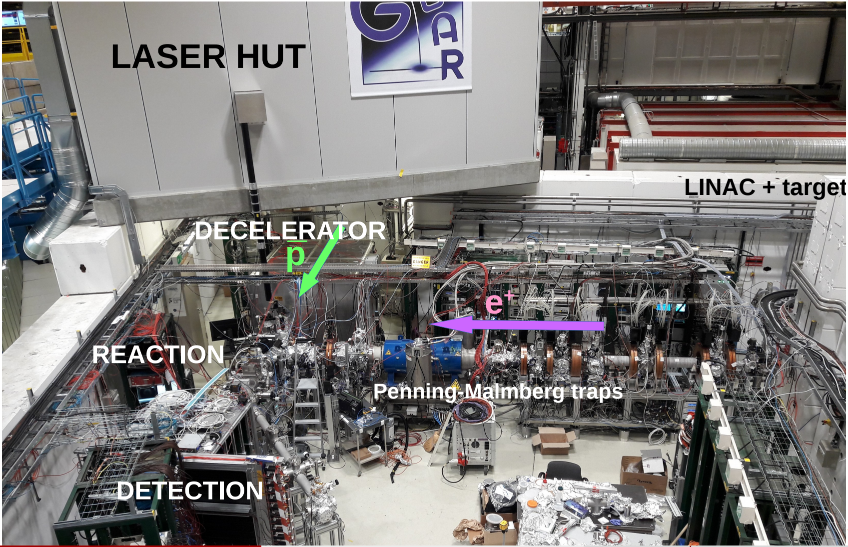


The scheme of the GBAR experiment



The GBAR zone

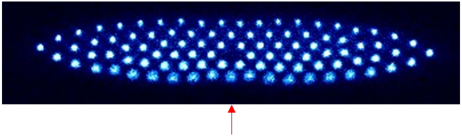
- summer 2018 - the first GBAR antiproton beam time



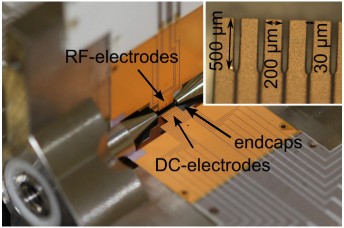
$\bar{H}^+$ cooling

- 1st step:
  - a mm scale RF linear trap;
  - capture and sympathetic Doppler cooling of a $\bar{H}^+$ ion in a big Be^+ crystal;
  - few mK.
- 2nd step:
  - miniaturized trap called precision trap;
  - ground state Raman side band sympathetic cooling of a $\mathrm{Be}^+/\bar{H}^+$ ion pair in the precision trap;
  - 10 μK.
- Hilico et al., Int. J. Mod. Phys. Conf. Ser. 30, 1460269 (2014).

N. Silitoe et al., JPS Conf. Proc. 18, 011014 (2017).



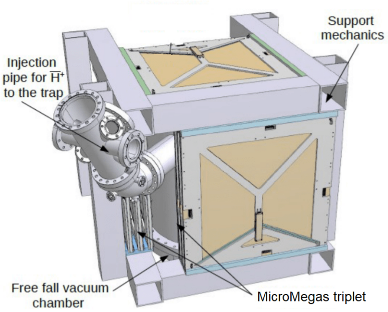
dark ion in capture trap (H_2^+ or H_3^+)

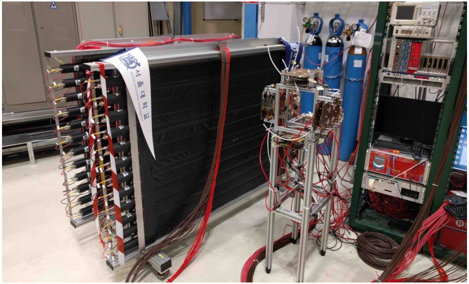


- *Precision trap.*

Free fall chamber and annihilation detectors

- Antihydrogen annihilation detectors:
  - tracker detectors - MicroMegas detectors 50 cm *x* 50 cm; the efficiency better than 96% per plane for charged pion;
  - Time of Flight Detectors build from bars made of scintillator - 170 cm *x* 10cm *x* 5cm, time resolution 80 ps.
- Magnetic field shield ($|\bigtriangledown B| \ll 2 \times 10^{-6}$ T/m) - under investigation.



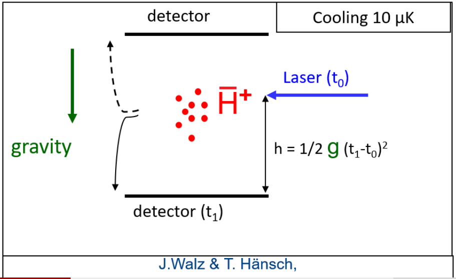


Gravitational Behaviour of Antihydrogen at Rest

- All these "small" elements described above have to work at the same time!:)
- 1 event gives 37% uncertainty, and 1500 events 1% ($h = 10$ cm $\rightarrow t = 0.14$ s, $\Delta t < 150$ μs, $\Delta h < 100$ μm).
- Precision: the main uncertainty on g comes from the energy and the energy dispersion of the initial beam (in this case $\Delta E = 1$ μeV).

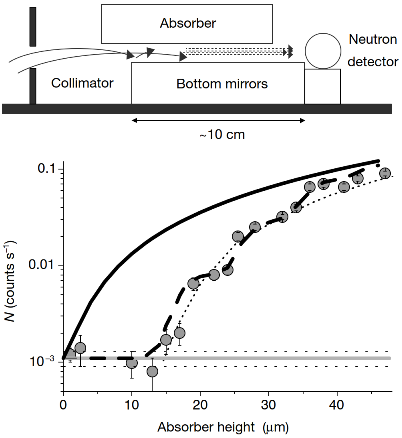
$$\frac{\Delta g}{g} \approx \frac{1}{\sqrt{N}} \sqrt{\left(\frac{\Delta h}{h}\right)^2 + \left(\frac{2\Delta t}{t}\right)^2}$$

$$\Delta h = \sqrt{(\Delta h)^2 + (\Delta h_0)^2 + (\Delta v_{h0} t)^2} \rightarrow \Delta v_{z0} = \sqrt{\frac{kT}{m_H} + \frac{2 m_e \Delta E}{5 m_H^2}}$$



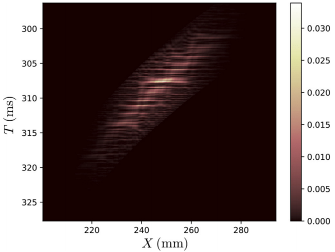
Gravitational quantum states (GQS)

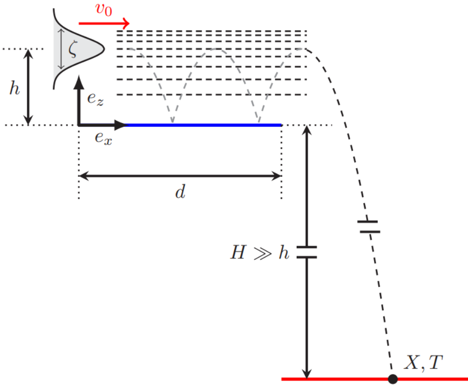
- Valery V. Nesvizhevsky et.al., Nature volume 415, pages297–299(2002). GRANIT collaboration.
- Neutrons are trapped by Casimir forces from below and gravitational forces from above. In this potential well they have quantized energy levels.
- Casimir-Polder force - a manifestation of the electromagnetic quantum fluctuations which are coupled to the atomic dipole.
- Ultracold neutrons total velocity - 10 m/s (neV); vertical velocity - 1.7 cm/s (peV).
- Lowest quantum state $\approx$ 15 μm.



Spectroscopy of the gravitational quantum levels of the $\bar{\mathrm{H}}$

- Proposal for antihydrogen: A. Yu. Voronin, P. Froelich, V. V. Nesvizhevsky, Physical Review A 83, 032903 (2011)).
- Recent estimations for the quantum interference technique - P.-P. Crépin et al., Phys. Rev. A 99, 042119 (2019).
- Down to 10^{-5} precision with 800 events, 10 μm first quantum gravitational level.





- Probability current density.

- In the meantime - GRASIAN collaboration for hydrogen bouncing.

Outline of the presentation

Clock experiments

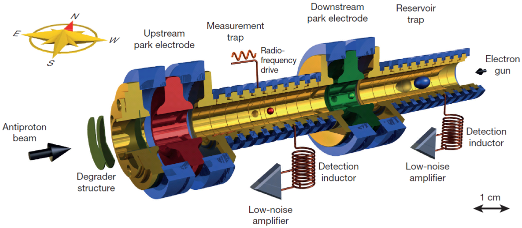
- Universality of clocks - all dynamical systems which can be viewed as clocks (e.g. (anti)atomic transition frequencies. frequency of (anti)particle motion in the Penning trap) measure the same gravitational time dilation independently of their composition (WEPc).
- Principle: any oscillator in a gravitational potential U experience a frequency red-shift.
- Trap clocks:
  - $\bar{p}$ (BASE); e^{+}; $\bar{\mathrm{H}}^{+}$ (GBAR).
- Spectral frequencies clocks:
  - $\bar{\mathrm{H}}$ (ALPHA, ALPHAg); $\bar{\mathrm{H}}_2^{-}$; $\bar{p}\mathrm{He}^{+}$ - antiprotonic helium (ASACUSA); Ps; Mu.

BASE experiment

- CPT is invariant, gravitational potential $U = 0 \Rightarrow$

$$\frac{q_p}{m_p} = \frac{q_{\bar{p}}}{m_{\bar{p}}} \quad \Rightarrow$$

$$\nu_{c,p} = \frac{q_p B}{2\pi m_p} = \frac{q_{\bar{p}} B}{2\pi m_{\bar{p}}} = \nu_{c,\bar{p}}$$



- Gravitational potential for protons U, for antiprotons $\alpha_g U$, where $\alpha_g \neq 1 \Rightarrow$ different gravitational red-shift for p and $\bar{p}$. $\Rightarrow$ Different cyclotron frequencies.
- Detection through proton/antiproton cyclotron frequency measurements:

$$\frac{\nu_{c,\bar{p}}}{\nu_{c,p}} = \frac{m_p}{m_{\bar{p}}} \left(1 + \frac{3(\alpha_g - 1)}{c^2} U\right)$$

R. J. Hughes, and M. H Holzscheiter, Phys. Rev. Lett.66, 854 (1991).

BASE experiment - results

- S. Ulmer et al., Nature 524 (2015) 196.
- Result of 6500 proton/antiproton q/m comparisons:

$$\frac{(q/m)_{\bar{p}}}{(q/m)_p} - 1 = 1(69) \times 10^{-12}.$$

- Assuming CPT invariance, for the local galaxy supercluster gravitational potential $U = 3 \times 10^{-5}$ this sets a limit for

$$\alpha_g < 8.7 \times 10^{-7}.$$

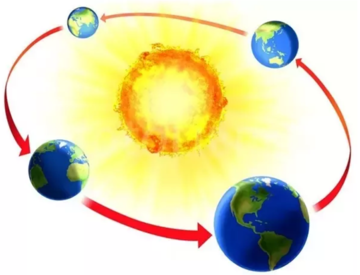
- However (!), are we sure about that value of the gravitational potential?

BASE - differential experiment

- Differential measurement sensitive to potential changes ΔU.
- ΔU on the surface of Earth due to its elliptic trajectory around the sun.
- One year long, high sampling rate experiment:

$$\frac{\nu_{c,\bar{p}}(t)}{\nu_{c,p}(t)} = \frac{m_p}{m_{\bar{p}}}\left(1 + \frac{3(\alpha_g - 1)}{c^2}\Delta U(t)\right).$$

  where $\Delta U = 10^{-9}(\alpha_g - 1)cos(2\pi t/365.25)$.
- Possible fractional resolution of $\Delta g/g = 6$ %.

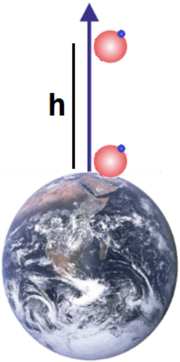


Atomic spectral frequencies - ALPHA experiment

- The ALPHA experiment is able to measure the atomic spectral frequencies at the level of 2 ppt (1S-2S), Nature, 557, 71, (2018).
- The atomis transition is measured with a laser, which is using a co-located Cs atomic clock - there will be no effect, if we measure just one atom in the same position.
- Solution - ALPHAg with an upper and lower trap. The antihydrogen 1S-2S transitions should be measured simultaneously with the same reference clock.
- Ratio of frequencies:

$$\frac{\Delta\nu}{\nu} = -\frac{GM_E h}{R_E^2} = -1.1 \times 10^{-16}\frac{h}{1m}.$$

- Current hydrogen experiments are at the level of 10^{-15}. They would require 10 m distance between hydrogen atoms.
- There is a bit to do...



Outline of the presentation

Summary

- The antimatter physics developed very strongly within the last 30 years.
- There are two basic approaches to test the Weak Equivalence Principle for antimatter:
  - free-fall experiments - antihydrogen, positronium muonium;
  - clock experiments.
- Current expected precision limit achievable within 2 years for free fall experiments is at the level of 1%. In the future down to 10^{-5}.
- Clock estimations of WEP performed by BASE give a good argument, that there will be no WEP violation above 10^{-6}. A possible differential measurement has the potential to reach about 6% accuracy.
- Viable theoretical models predict any WEP violation below 10^{-7}, so there is still a lot to do!

Thank you for your attention!

Available antimatter particles/systems

- Single particles:
  - e^+;
  - $\bar{p}$.
- Neutral systems:
  - Ps - positronium - the bound state of an electron and a positron (para-positronium - 125 ps; ortho-positronium 142 ns lifetime);
  - Mu - muonium - the bound state of an antimuon and an electron (2.2 μs lifetime);
  - $\bar{\mathrm{H}}$ - antihydrogen - an atom made from a positron orbiting around a nucleus composed of one antiproton (stable!);
  - $\bar{p}^4\mathrm{He}^+$ - antiprotonic helium - an atom made from one electron, one antiproton and a helium nucleus (3 μs lifetime).
- Charged systems (hopefully soon):
  - $\bar{\mathrm{H}}^+$ - antihydrogen anion - an ion made from two positrons orbiting around a nucleus composed of one antiproton (stable!);
  - $\bar{\mathrm{H}}_2^-$ - antihydrogen molecule.