Weighting Antihydrogen

3 experiments at CERN are about to « weight » antihydrogen atoms
AEgIS → Pierre Lansonneur, ALPHA, GBAR → Paul Indelicato

- **Objective**
- **Motivation**
  - ✓ **Theory**
  - ✓ **Experiment**
- **Conclusion**

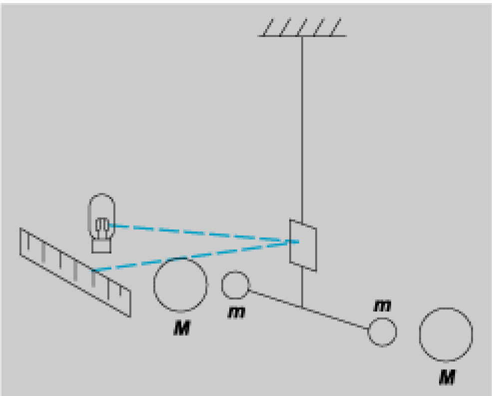
Objective

<u>A direct test</u> of the Equivalence Principle with antimatter

The acceleration imparted to a body by a gravitational field is independent of the nature of the body :

Inertial mass = gravitational mass

Tested to a very high precision with many materials



Weak Equivalence Principle (torsion pendulum)

$$(\Delta a / a)_{Be/Ti} = (0.3 \pm 1.8) \times 10^{-13}$$

S.Schlamminger et al, Phys Rev Lett 100 (2008) 041101

Strong Equivalence Principle (Lunar Laser Ranging)

$$(\Delta a / a)_{Earth/Moon} = (-1.0 \pm 1.4) \times 10^{-13}$$

J.G.Williams et al, Phys Rev Lett 93 (2004) 261101

The measured parameter: $\bar{g}$

Gravitational acceleration on Earth of antihydrogen atoms

apple **antiapple**

$$F_z = G\frac{M_T}{R_T^2} m_g$$

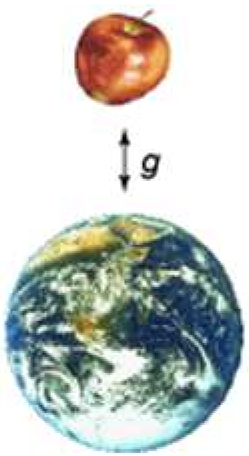
$$F_z = m_i a$$

$$g \equiv a = \frac{F_z}{m_i} = G\frac{M_T}{R_T^2} = 9{,}8\, m/s^2$$

$\uparrow$

$\boxed{m_g = m_i}$

Equivalence principle



Earth

z

Earth

$$\bar{F}_z = G\frac{M_T}{R_T^2}\bar{m}_g$$

$$\bar{F}_z = \bar{m}_i \bar{a}$$

$$\boxed{\bar{g}} \equiv \bar{a} = \frac{\bar{F}_z}{\bar{m}_i} = G\frac{M_T}{R_T^2}\frac{\bar{m}_g}{\bar{m}_i} = g\frac{\bar{m}_g}{\bar{m}_i}$$

$\boxed{???\ \bar{m}_g = \bar{m}_i\ ???}$

Antimatter

particules			antiparticules		
electron	e^-	•	•	e^+	positron
proton	p	⊕	⊖	$\bar{p}$	antiproton
neutron	n	○	○	$\bar{n}$	antineutron
photon	γ	•	•	γ	photon

Same inertial mass
Same lifetime
Opposite charges

CP violation (1964) J. Christenson, J. Cronin, V. Fitch, R. Turlay:
Decay rates of particles and antiparticles to CP even states can be (slightly) different
Example: $\Gamma\left(K^0 \rightarrow \pi^+\pi^-\right) \neq \Gamma\left(\overline{K}^0 \rightarrow \pi^+\pi^-\right)$

➔ **∃ small matter antimatter differences in the Standard Model**

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Antimatter&gravitaion
Theory (1)

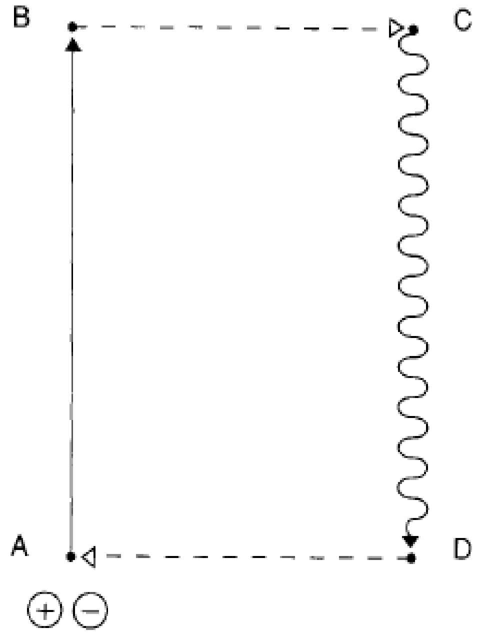
Morrison argument (1958):
antigravity in General Relativity
(or any difference between matter and antimatter)
$\rightarrow$ violation of energy conservation

$$\text{if } m_G(+) = -m_G(-):$$

$$E_A = E_B = 2m_I c^2 = h\nu_C$$

$$h\Delta\nu_{CD} = h\nu_C (gL/c^2) = 2m_I gL$$

$$E_D = E_A + 2m_I gL$$



Theory (2)

Supergravity:
→ new gravi-scalar and gravi-vector fields coupled to baryon number
→ distinguish m_G and $\overline{m}_G$
J. Scherk, Phys. Lett. B (1979) 265, S. Belluci & V. Faraoni Phys. Lett. B (1996) 55

$$V = -G\frac{mm'}{r}(1 \underbrace{\mp a\,\exp(-r/v) + b\,\exp(-r/s)}_{\text{supergravity : one repulsive contribution}})$$

Tests with matter give only limits on ~ |b-a|

But exact cancellation scalar/vector impossible (4-velocity dependance)
D.S.M. Alves et al SU-ITP-09/36

Theory (3)

Antimatter content of ordinary matter (Schiff argument)

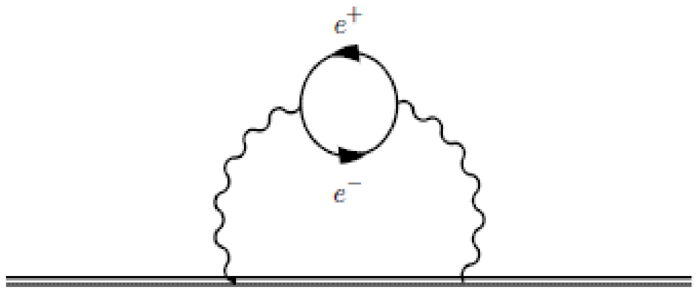


FIG. 2: Loop contribution to the electrostatic self-energy of the nucleus

$$\left|\frac{g-\bar{g}}{g}\right| \sim \left|\frac{g-g_{\Delta Erad}}{g}\right| \Rightarrow$$

Scenario	Argument	Bound on $\lvert g_H - g_{\bar{H}}\rvert / g_H$
Modification of GR	Lamb shift	$\lesssim 10^{-2}$
	Electrostatic self-energies of nuclei	$\lesssim 10^{-7}$
	Antiquarks in nucleons	$\lesssim 10^{-9}$
Scalar-vector	Radiative damping of binary systems	$\lesssim 10^{-4}$
	Scalar charges are not vector charges	$\lesssim 10^{-8}$
	Velocity dependence	$\lesssim 10^{-7}$

D.S.M. Alves et al SU-ITP-09/36

Theory (4)

Standard Model Extension (*Kostelecky et al*):

- models for analysis of CPT&LI tests escape these arguments

  J.D. Tasson Int. J. Mod. Phys. Conf. Ser. 30, 1460273 (2014)

- but are sensitive to other tests

  atomic interferometry

  kinetic energy bound systems (nuclei) …

- $(\bar{g}-g)/g < 10^{-6} - 10^{-8}$

- but model dependant limit

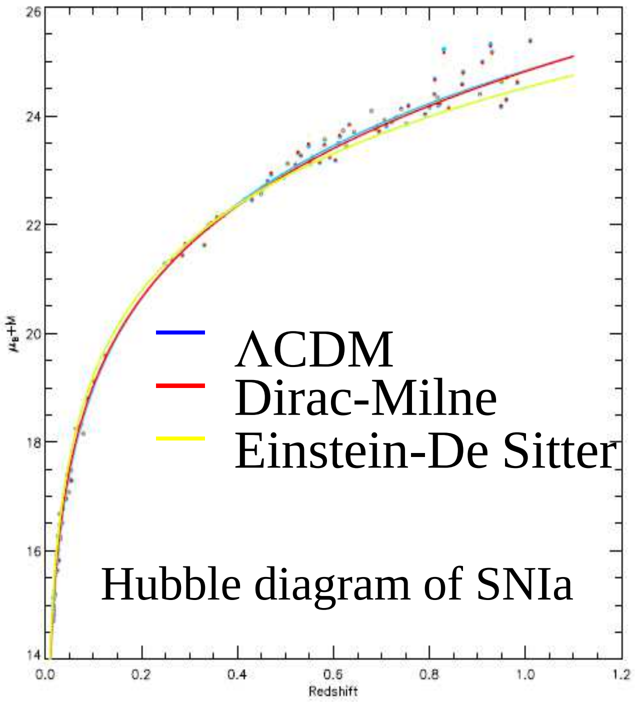
  M. Hoensee et al, Phys.Rev.Lett. 111, 151102 (2013)

Other models → see WAG 2015

Cosmology

- Matter-antimatter asymmetry in the Universe ???
- Cannot be explained by CP violation in the standard model
- GR OK (at cosmological scales) but with dark energy, dark matter and inflation… and tensions at small scales

→ need new model ?



Hubble diagram of SNIa

Could there be a matter-antimatter repulsive force?

→ Dirac Milne Universe

Attempt to build a cosmology with:

- Matter-antimatter symmetry
- Mechanism to separate matter from antimatter

PhD Thesis Paris XI, A. Benoît-Lévy – dir G. Chardin (2009)

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Experiments: indirect limits (1)

Study CP violation parameters $\eta^{\pm}$ et $\Phi^{\pm}$ of the K^0-$\overline{K}^0$ system

as a function of time (CPLEAR)

K^0-$\overline{K}^0$ oscillations depend on $$\delta m_{eff} = M_{K^0} \left(\frac{g - \overline{g}}{g} \right)_I \frac{GM}{rc^2} \exp(-r / r_I) f(I)$$

(A. Apostolakis et al., Phys Lett B 452 (1999) 425)

Summary of limits on $\left| \frac{g - \overline{g}}{g} \right|$ for spin 0, 1 and 2 interactions

Source	Spin 0	Spin 1	Spin 2
Earth	6.4×10^{-5}	4.1×10^{-5}	1.7×10^{-5}
Moon	1.8×10^{-4}	7.4×10^{-5}	4.8×10^{-5}
Sun	6.5×10^{-9}	4.3×10^{-9}	1.8×10^{-9}
Galaxy	1.4×10^{-12}	9.1×10^{-13}	3.8×10^{-13}
Supercluster	7.0×10^{-14}	4.6×10^{-14}	1.9×10^{-14}

Potential variation with time (Earth, Moon, Sun)

Need an absolute potential → (Galaxy, Supercluster)

Experiments: indirect limits (2)

Cyclotron frequency of p (H^-) and $\bar{p}$ in the same B

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

G. Gabrielse et al. Phys Rev Lett 82 (1999) 3198

$$\omega = qB/2\pi m + \alpha \underbrace{U/c^2}_{\text{local supercluster}} \qquad |\omega - \bar{\omega}|/\omega = (9 \pm 9)\,x10^{-11} \rightarrow |g - \bar{g}|/g \leq 10^{-6}$$

Experiments: a direct limit ?

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

post-newtonian parameter (1 in GR)

$$\text{gravitational delay} : \delta t = MG\left[-R/\sqrt{R^2+b^2} + (1+\gamma)\ln\left|R+\sqrt{R^2+b^2}/b\right|\right]$$

$$|\delta t(\upsilon_e) - \delta t(\bar{\upsilon}_e)|/\delta t(\bar{\upsilon}_e) < 10^{-6} \rightarrow |\gamma(\upsilon_e) - \gamma(\bar{\upsilon}_e)|/\gamma(\bar{\upsilon}_e) < 10^{-6}$$

(*S. Paksava et al. Phys Rev D 39 (1989) 1761*)

Past attempts and proposals (1)

- **positrons** : *F. Witteborn and W. Fairbank, Phys Rev Lett 19 (1967) 1049)*

  Very difficult: $m_e g / e = 5.6x10^{-11} V / m$ (one elementary charge at 5 m)

- **antiprotons** : *PS200 Proposal Los Alamos Report LA-UR 86-260 but could not be performed*

- **antineutrons** : difficult to slow down

  T. Brando et al, NucI. Instrum. Methods 180 (1981) 461

Past attempts and proposals (2)

- **positronium**: bound e^+ - e^- system → neutral system

short life time (142 ns) if n = 1
Lifetime OK if excited n>>1 $\tau \simeq (n/25)^{5.236} \times 2.25\,\text{ms}$

But high polarisability → sensitivity to stray electric fields

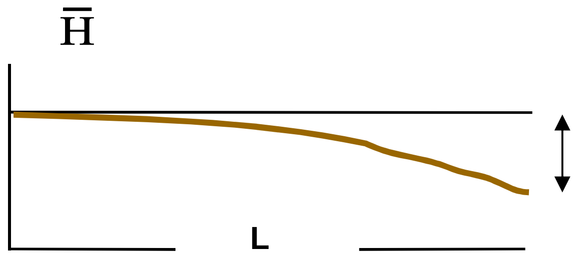
Pbs : cooling, ionisation from thermal radiation…
A.P. Mills, M. Leventhal, NucI. Instrum. Meth. in Phys. Research. B192 (2002) 102

Project by D. Cassidy at Cambridge UK
described in G. Dufour et al, Adv. In High Energy Physics 2015 (2015) 379642

Next simplest system: $\bar{\mathrm{H}}$

Principle for ~% measurement:

Parabolic flight of $\bar{H}$



$$h = \frac{\bar{g}}{2}\left(\frac{L}{v_h}\right)^2$$

- L = 2 cm et v_h ~ 100 m/s (E($\bar{\mathrm{H}}$) $\lesssim$ 540 mK ~ 50 μeV)

  $\longrightarrow$ *ALPHA: - atoms* $\bar{\mathrm{H}}$ *(neutral)*

- L = 1 m et v_h ~ 500 m/s $\longrightarrow$ h = 20 μm (T($\bar{\mathrm{H}}$) ~ 100 mK ~ 10 μeV)

  $\longrightarrow$ *AEGIS: - atoms* $\bar{\mathrm{H}}$ *(neutral)*

- L = 0.1 m et v_h = 0.5 m/s $\longrightarrow$ h = 20 cm (T($\bar{\mathrm{H}}$) ~ 10 μK ~ 1 neV)

  $\longrightarrow$ *GBAR:* **cold $\bar{\mathrm{H}}^+$** $\longrightarrow$ very slow $\bar{\mathrm{H}}$

Objective in a first step: $\Delta\bar{g}/g$ of order a few 10^{-2}

ARTICLES
PUBLISHED ONLINE: 5 JUNE 2011 | DOI: 10.1038/NPHYS2025

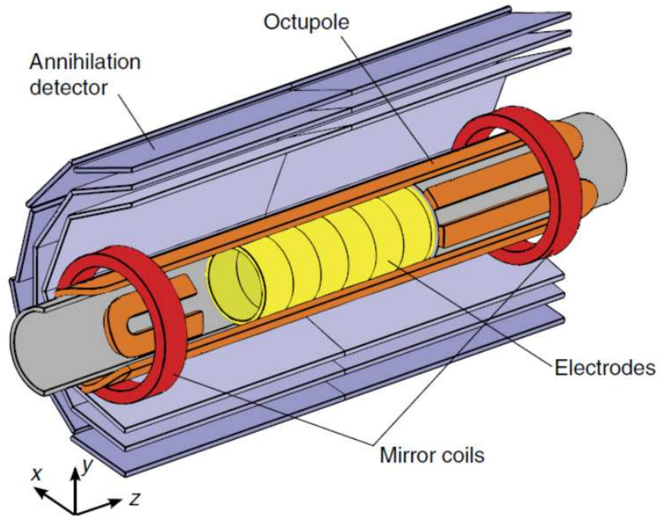
nature physics

Confinement of antihydrogen for 1,000 seconds

The ALPHA Collaboration*

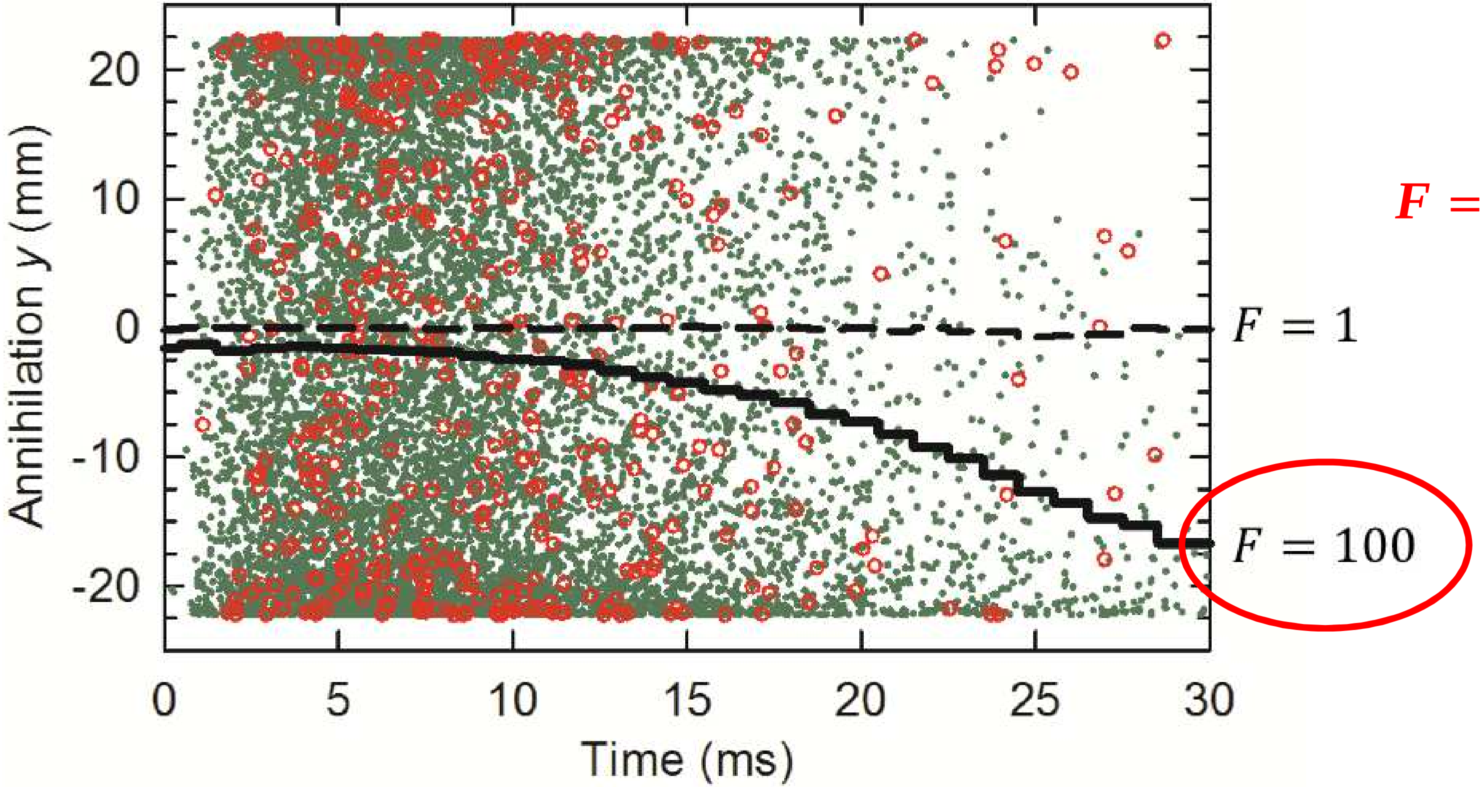
Atoms made of a particle and an antiparticle are unstable, usually surviving less than a microsecond. Antihydrogen, made entirely of antiparticles, is believed to be stable, and it is this longevity that holds the promise of precision studies of matter–antimatter symmetry. We have recently demonstrated trapping of antihydrogen atoms by releasing them after a confinement time of 172 ms. A critical question for future studies is: how long can anti-atoms be trapped? Here, we report the observation of anti-atom confinement for 1,000 s, extending our earlier results by nearly four orders of magnitude. Our calculations indicate that most of the trapped anti-atoms reach the ground state. Further, we report the first measurement of the energy distribution of trapped antihydrogen, which, coupled with detailed comparisons with simulations, provides a key tool for the systematic investigation of trapping dynamics. These advances open up a range of experimental possibilities, including precision studies of charge–parity–time reversal symmetry and cooling to temperatures where gravitational effects could become apparent.

ALPHA



First direct limit on $\bar{g}$

Antihydrogen $F = M_G / M$



$F = \left| \frac{\bar{g}}{g} \right| \sim \leq 110$

Green dots---simulated annihilations

Red circles---434 Observed annihilations

Vertical position of annihilation vertex during release of trapping field

The ALPHA collaboration
Nature comms 2013 (4:1785 | DOI: 10.1038/ncomms2787)

- **Objective**

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- **Conclusion**

Conclusion: Theory

- “In conclusion whether or not one now accepts the existence of non-Newtonian gravitational forces, the possibility of new non-inverse-square and/or composition-dependent components of gravity **must be thoroughly studied**”

  Nieto – Goldman *PHYSICS REPORTS (Review Section of Physics Letters) 205, No. 5(1991)*

- However **expected effects are quite small**

- A 1 % experiment is a “textbook experiment” **and should be a first step towards higher precision**

Conclusion: $\bar{\text{H}}$ Experiments

- **ALPHA:**
  - **has put first direct limits on $\bar{g}$**
  - **has a project to do a first ~10% measurement with a vertical detector**
  - **has a long term project for a precise measurement with interferometry**
- **AEGIS has crossed important steps towards a ~% measurement**
- **GBAR is just starting installation at CERN and aims at measuring $\bar{g}$ to $10^{-2} \rightarrow 10^{-4}$ - 10^{-6} (?) precision**

All these experiments are very challenging !