ADVANCES TOWARDS A DIRECT MEASUREMENT OF THE GRAVITATIONAL INTERACTION ON ANTIMATTER WITH THE AEg IS EXPERIMENT

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□ Universality of free fall (UFF) established by Galileo and Newton

 $m_i = m_g$

Weak equivalence principle (WEP)

	electric field:	gravitational field:
Unique behavior:	$\mathbf{F} = q \cdot \mathbf{E}$	$\mathbf{F} = m \cdot \mathbf{G}$
	$ \mathbf{E} \propto rac{Q}{r^2}$	$ {f G} \propto {M \over r^2}$
	$ \mathbf{a} \propto q$	$ \mathbf{a} = const$

□ Einstein Equivalence Principle:

- WEP
- Local Lorentz Invariance (LLI)
- Local Position Invariance (LPI)



TEST OF THE EEP

□ EEP is the *"heart and soul"* of **General Relativity (GR)**:

EEP valid → gravity is governed by a "metric theory of gravity"

R. Dicke, Les Houches Summer School of Theoretical Physics: Relativity, Groups and Topology, pp. 165–313, CNUM: C63-07-01 (1964)

□ EEP extensively tested experimentally:

C. Will, Living Rev. Relativity 17 (2014)

Isotropy of atomic energy levels: $\delta = |c^{-2} - 1| > 10^{-23}$

Gravitational red shift:

$$\frac{\Delta \nu}{\nu} = (1 + \alpha) \frac{\Delta U}{c^2} > 10^{-6}$$

Torsion balance:

$$\eta = \frac{a_1 - a_2}{(a_1 + a_2)/2} > 10^{-13}$$



WEP FOR ANTIMATTER: THE CURRENT PICTURE

- □ Some arguments *would* suggest the WEP holds for antimatter
- □ Strong theoretical arguments only apply to the idea of *antigravity*
 - Morrison (1958), Schiff (1958), Good (1961), etc...
 - none of them *necessarily* requires $m_i^{anti-matter} = m_g^{matter}$
- □ On the experimental side:

neutrinos detected from Supernova 1987A

S. Pakvasa *et al.*, **Phys. Rev. Lett. D.** 39, 6 (1989)

Shapiro delay of relativistic particles not a test for the EEP

G. T. Gillies, Class. Quantum Grav. 29 (2012)

 $\Box p - \bar{p}$ cyclotron frequency comparisons: $(\omega_c - \bar{\omega}_c)/\omega_c < 9 \cdot 10^{-11}$

G. Gabrielse et al., PRL 82 (3198) (1999)

• Model dependent, CPT assumption, absolute potentials, ...

□ and others...but none of them is conclusive

WEP FOR ANTIMATTER: WHY TO TEST IT?

Our attempts for a quantum theory of gravity typically result into new interactions which violate the WEP (ex. KK theory)

Int. J. Mod. Phys. D18, 251–273 (2009)

 Some open questions (like *dark matter* and *baryogenesis*) could benefit from a direct measurement
 Astrophys. Space Sci. 334, 219–223 (2011)

JHEP 1502, 076 (2015)

Because it's possible and no direct measurements are available

□ Previous attempts:

1967: Fairbank and Witteborn tried to use positrons

Phys. Rev. Lett. 19, 1049 (1967)

• **1989**: PS-200 experiment at CERN tried to use (4 K) \bar{p}

Nucl. Instr. and Meth. B, 485 (1989)

- Both **unsuccessful** because of stray \vec{E} and \vec{B} fields
- 2013: ALPHA experiment at CERN set limit on m_g/m_i for \overline{H}

• $m_g/m_i > 110$ excluded at 95% CL

Nature Communications 4, 1785 (2013)

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GRAVITY MEASUREMENT WITH $AE\overline{g}IS$ EXPERIMENT

Main goal of AEgIS: a direct measurement of the Earth's local gravitational acceleration g on a "cold" beam of H atoms using a moiré deflectometer



□ For \overline{H} at very low temperature a precision of the order of few percent could be reached

AEgIS APPARATUS



(Over)Simplification of the experimental setup





ANTIHYDROGEN PRODUCTION STRATEGY

- □ *Standard* way to produce \overline{H}^* atoms (used by other experiments):
- AEgIS aims at producing cold antihydrogen through a charge exchange reaction:
- □ Large cross section: $\sigma \propto n_{Ps}^4$ ($n_{Ps} \approx 20 30$)
- □ AEgIS strategy:
 - Capture of \overline{p} coming from AD
 - Electron cooling of trapped \overline{p}
 - □ Ps production via e^+ on SiO_2 target
 - □ Ps laser excitation to Rydberg states







$$(Ps^* + \bar{p} \longrightarrow \bar{H}^* + e^-)$$

Rydberg positronium

POSITRONIUM FORMATION AND EXCITATION

- Ps produced via electron capture of e⁺ within a nanoporous silica target
- Two-step in-flight laser excitation of Ps (demonstrated in our paper Phys. Rev. A 94 (2016) 012507):
- $UV: n = 1 \rightarrow 3$ $IR: n = 3 \rightarrow Rydberg$





TOWARD THE MEASUREMENT OF g on \overline{H}

 \Box A lot of work done on \overline{p} (catching, cooling, manipulation and transfer)



- □ on *Ps* (spectroscopy of $1 \rightarrow 3$ and $3 \rightarrow 15$ transitions, development of a long-lived source of $2^3S Ps$, $2^3S Ps$ from stimulated 3^3P decay,...) and its diagnostics
- on detectors (scintillators, nuclear emulsions, Timepix,...)





ANTIHYDROGEN ANALYSIS STRATEGY

 \Box Evidence of \overline{H} production searched with a counting experiment



- Counts are detected with the surrounding organic scintillators in a fixed time interval
- Coincidence between the PMTs signals from both ends is performed



ANTIHYDROGEN ANALYSIS STRATEGY

- $\Box \gamma/\pi$ discrimination by cutting on the amplitude of the digitized signals
- Possible sources of background (p
 losses, cosmic rays, degassing, ...)

 estimated using dedicated data sets
 with and without e⁺ and/or laser
- Results submitted for publication
- In the past we also tested the working principle of the experiment
- We used a small-scale moiré deflectometer and a beam of cold \overline{p}







RESULTS: (MINI) MOIRÉ TEST WITH ANTIPROTONS

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CONCLUSIONS AND FUTURE PLANS

- \Box AE $\bar{g}IS$ aims at probing the WEP on antimatter
 - No direct measurement so far

 \square Several milestones achieved on \overline{p} and Ps manipulation

- $\hfill\square$ The working principle of the experiment tested using \overline{p}
 - Stray *B* field \rightarrow no gravity measurement possible on \overline{p}

Goal

Results

Results on *H* production submitted for publication
 First gravity measurements planned for the next years
 Longer term plans also include *H* - *H* spectroscopy