AEgIS experiment at CERN: measuring antihydrogen free-fall in Earth's gravitational field to test WEP with antimatter

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Abstract. The AEgIS (Antimatter Experiment: Gravity, Interferometry, Spectroscopy) experiment is designed with the objective to test the weak equivalence principle with antimatter by studying the free fall of antihydrogen in the Earth's gravitational field. A pulsed cold beam of antihydrogen will be produced by charge exchange between cold Ps excited in Rydberg state and cold antiprotons. Finally the free fall will be measured by a classical moirè deflectometer. After the description of the apparatus being assembled at the Antiproton Decelerator at CERN, the advancements of the experiment will be reported.

1. Introduction

The weak equivalence principle (WEP), also known as universality of free fall (UFF), states that in a gravitational field all bodies, irrespective of their mass and composition, fall with the same acceleration. UFF of matter in the field of Earth has been tested by measuring the dimensionless parameter $\eta = \Delta a/a$ where Δa is the relative acceleration between two proof masses as they fall with an acceleration a towards the Earth; validity of UFF-WEP requires $\eta = 0$. Precision experiments with torsion balance and dropping of cold-atoms have measured η reaching values of $\cong 10^{-13}$ and $\cong 10^{-7}$, respectively [1].

Up to now, in spite of very precise experiments done with matter, none has been carried out to test UFF-WEP with antimatter.

AEgIS experiment, set up at the Antiproton Decelerator (AD) at CERN, is designed with the primary scientific goal of measuring for the first time the free fall of antihydrogen ($\overline{H}$) in the gravitational Earth's field with a precision of 1% [2]. In the experiment the $\bar{g}$ measurement will be carried out measuring the time of flight and the vertical displacement of each $\overline{H}$ after its passage through a moiré deflectometer realized with two gratings and a position sensitive detector. The needed pulsed cold beam of $\overline{H}$ will be produced by charge exchange among excited Ps atoms and cooled antiprotons.

The achieved progresses forming a cold antihydrogen beam and measuring gravity will be summarized.

2. AEgIS experiment: method and set-up

A detailed description of the experiment can be found in [3]. The method proposed by AEgIS to form the cold $\overline{H}$ beam is sketched in Fig. 1. Bunches of more than 10^8 positrons with a duration of about 10 ns are shot on a positron-positronium (Ps) converter. Collisional cooled Ps emitted into vacuum is excited in Rydberg states. These long living Ps fly into the antiproton trap, where $\overline{H}$ can be formed in an excited state by charge exchange reaction: $Ps^* + \overline{p} \rightarrow \overline{H}^* + e^-$. Ps excitation in high Rydberg states is necessary not only to lengthen its lifetime, but also to augment the $\overline{H}^*$ yield: the cross section of the charge exchange reaction is proportional to n^4 where n is the *Ps* principal quantum number. Finally, excited $\overline{H}^*$ are Stark accelerated towards a moiré deflectometer, the classical analog of a matter wave interferometer. Along its travel $\overline{H}^*$ decay to ground states.

A sketch of the moirè deflectometer is shown in Fig. 1. The present design is based on a device previously used to measure the gravity acceleration of an argon beam with high sensitivity [4].

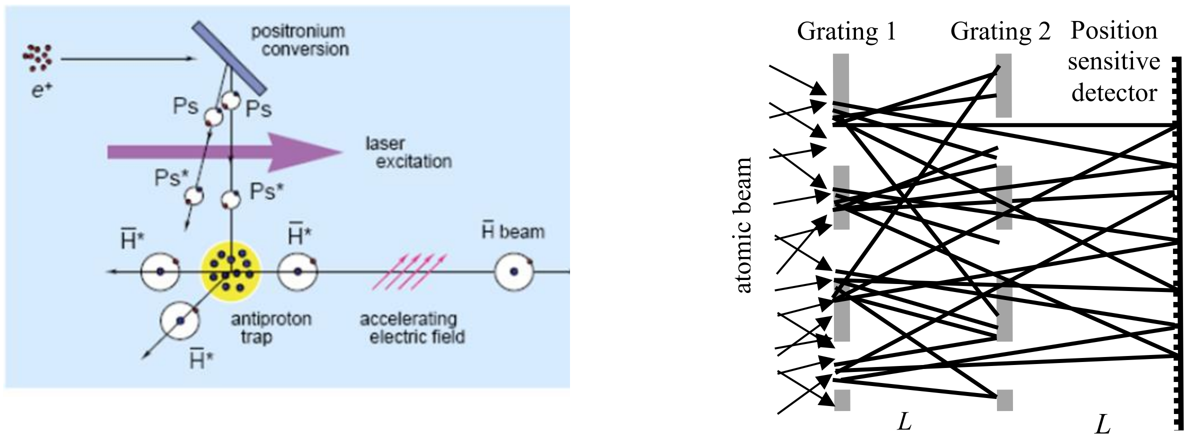

Fig. 1: Left, AEgIS method for the production of a pulsed cold $\overline{H}$ beam; Right, sketch illustrating the moiré deflectometer technique: a divergent $\overline{H}$ beam ($v \sim 400 - 600\,m\,s^{-1}$) propagates through two identical gratings with a 80 μm period at a distance L=40 cm. $\overline{H}$ passing the gratings follow a parabolic path and annihilate on a position sensitive detector with a 10 μm downward shift.

The experimental apparatus scheme is shown in fig. 2, details in [5]. AD delivers bunches of ~ 3x10^7 $\bar{p}$ every ~ 110 s with 5.3 MeV kinetic energy. Antiprotons passing through aluminum foils (degrader) are slowed down to few keV and then caught in a 75 cm long set of Penning-Malberg traps in the 5 T magnet. Trapped $\bar{p}$ are cooled to few Kelvin by sympathetic cooling with a cloud of 10^7-10^9 electrons previously stored in a 100-150 V potential well (see section 3). Cooled $\bar{p}$ are then transferred in a second Penning-trap in the 1T magnet and there wait for *Ps* to form $\overline{H}$.

Positron, from a 22Na radioactive source (~10 mCi) coupled to a Ne moderator [6], are cooled in a two stages Surko buffer trap [7] and stored in a Penning-Malberg accumulator that releases bunches of some 10^7 e^+, that are then transferred and trapped in the 5T magnet.

Ps in vacuum is produced by transferring and implanting previously trapped positrons (see section 3) in a porous silica converter installed in the 1T magnet. UV (λ=205 nm) and IR (λ~1670 nm) laser light [8] is transported with glass fibers in front of the converter to perform a two steps *Ps* excitation: $1^3S \rightarrow 3^3P$, $3^3P \rightarrow Rydberg\ states$ (see section 4).

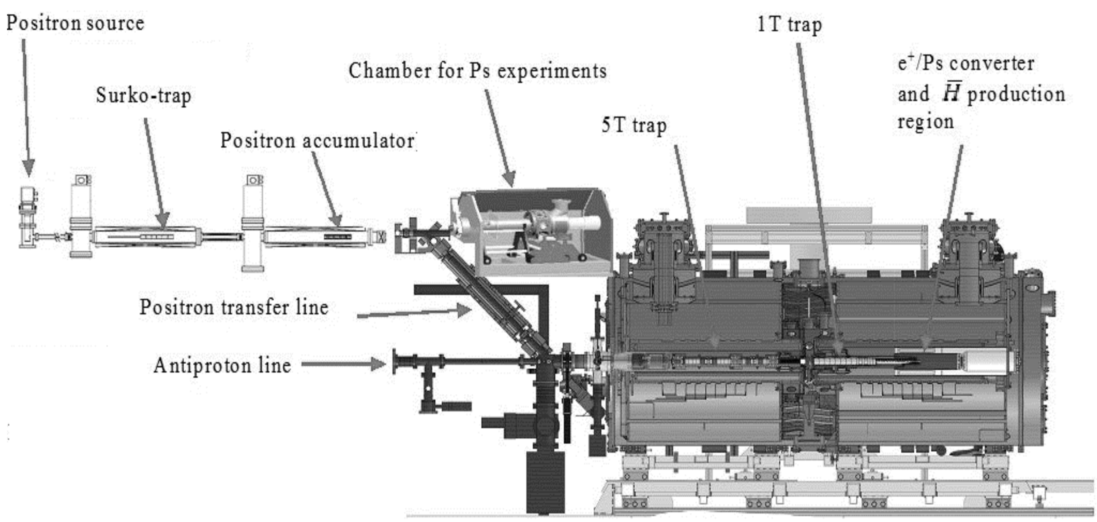

Fig. 2 Scheme of the AEgIS experimental set-up.

In addition to the main apparatus for $\overline{H}$ gravity study, a secondary chamber to perform *Ps* formation and excitation experiments is connected to the accumulator through a 60 cm magnetic transport line. Positrons pass through a magnetic field terminator and are bunched (~ 7 ns FWHM) and focused on a *Ps* converter with a spot of less than 4 mm FWTM; bunched positron energy varies in the 3 to 8 keV range [9, 10].

3. Trapping positrons and antiprotons in the 5T magnet

A reproducible procedure for trapping e^+ and $\bar{p}$ in the 5T region was devised during the 2015 AD run [5, 11]. Bunches of e^+, with a longitudinal velocity corresponding to an energy of 300 eV, were magnetically transported in a 0.14 T field and injected into the Penning-Malberg trap in a 4.5 T magnetic field. Positrons are cooled down by cyclotron radiation and trapped in a 50-100 eV potential well. Number of stored e^+ and e^+ lifetime in the trap were evaluated by dumping the particles on a stopper and measuring annihilation gammas with plastic scintillators placed around the 1T-5T chamber. When ~2.5×10^7 e+ are trapped, about 100% of them cool down without observed losses for storage times up to more than 30 min. Thanks to the long lifetime of e^+ in the trap, it was possible to accumulate more than 2×10^8 e^+, transferring shots of 1.8×10^7 e+ from the accumulator, see Fig. 3 .

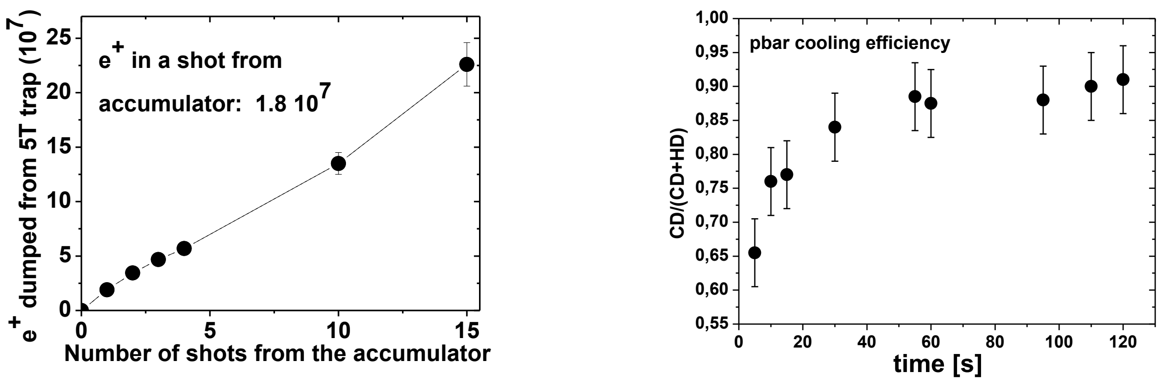

Fig. 3 Left: Trapped e+ in the 5T region as a function of number of shots from the accumulator. Right: fraction of cold $\bar{p}$ as a function of time spent in the trap with electrons.

Study of trapped $\bar{p}$ was done in the same Penning-Malberg trap used to store e^+. On the average 3.6×10^5 $\bar{p}$ were captured for each shot of 3.0×10^7 $\bar{p}$ delivered by AD, with an optimized 9 kV trapping potential. In Fig. 3, right panel, the fraction of cooled $\bar{p}$ (CD-cold dump, obtained dumping the low voltage of the trap) against the total trapped $\bar{p}$ CD+HD (HD-hot dump, dumping the high voltage of the trap) is reported as a function of the time spent by $\bar{p}$ with electrons. A cooling efficiency of 90% was achieved in about 60 s with an optimum overlap of the e^-- $\bar{p}$ clouds.

4. Positronium formation and excitation in the secondary chamber

The *Ps* formation, its emission into vacuum and its excitation in *Rydberg* states were proved and verified in the testing chamber [10] in line with the Surko trap and the accumulator, see Fig. 2.

High yield of Ps in vacuum was observed [10] using Si target with oriented oxidized nanochannells [12, 13] as e^+/Ps converters. *Ps* excitation was measured by the SSPALS (Single Shot Positron Annihilation Lifetime Spectroscopy) firstly introduced by Cassidy and Mills [14] to study two steps, $1^3S \rightarrow 2^3P,\ 2^3P \rightarrow Rydberg$ excitation [15], Ps-Ps interaction [16] and to observe Ps_2 molecule [17].

The lifetime spectra from the single gamma ray shots were acquired with a $PbWO_4$ scintillator coupled to Hamamatsu R11265-100 photomultiplier tube. A laser system to perform the two steps *Ps* excitation $1^3S \rightarrow 3^3P$, $3^3P \rightarrow Rydberg$ was designed and set up [8].

An UV laser pulse (205 nm, energy 54 µJ, time length ~ 1.5 ns) was used to excite *Ps* from ground to n=3 state and simultaneously an IR laser (λ=1064 nm, 50 mJ, 10 ns temporal length) was shot to ionize the excited Ps.

An IR laser (tuneable wavelength in the ~ 1650- ~1720 nm range, energy ~ 1mJ, time length ~4 ns) was pulsed at the same time with the UV laser to excite *Ps* from n=3 to Rydberg levels.

Results are shown in Fig. 4. Experiment details and analysis of the data are extensively reported in [18].

The black lines in Fig. 4, after the annihilation prompt peak, display the *Ps* decaying in vacuum. When the UV+IR (λ=1064 nm) lasers are shot on the *Ps* cloud, *Ps* population is decreased by the fraction of ionized *Ps* atoms, grey curve in the left panel of Fig. 4. The decrease is evaluated with the parameter $S\% = (f_{off}-f_{on})/f_{off}$ where f_{off} and f_{on} are the areas of the SSPAL spectra between 50 and 250 ns with the laser *off* and *on*. In the inset (left panel Fig.4) the the $1^3S \rightarrow 3^3P$ excitation linewidth obtained measuring $S\%$ as a function of the UV wavelength is shown.

Lifetime of Ps, when excited in Rydberg states, increases up to microseconds allowing $Ps*$ to reach the walls of the vacuum chamber. In this case SSPALS spectrum shows a decrease of annihilations after the prompt peak and an increase of annihilations when $Ps*$ start reaching the chamber walls, grey curve in the right panel of Fig. 4. A scanning of the IR laser, keeping UV laser wavelength constant on n=3 resonance (λ=205.05 nm), was carried out to resolve the n=15-17 Rydberg lines. The $-S\%$ calculated between 300-600 ns is reported in the inset (right panel Fig.4) as a function of IR wavelength.

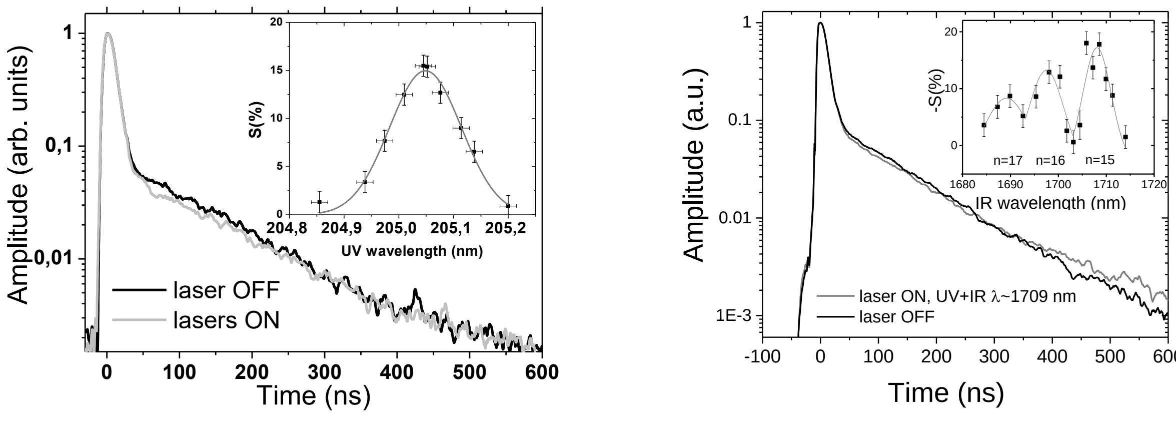

Fig. 4 SSPAL spectra. Left: *Ps* in vacuum, laser off , black line; laser (UV+IR) on gray line; in the inset the scanning with the UV wavelength, showing the n=3 excitation line. Right: *Ps* in vacuum, laser off , black line; laser (UV+IR) on gray line; in the inset the scanning with the IR wavelength, showing the *Ps* excitation in the n=15-17 Rydberg states.

5. Moiré deflectometer: concept proof with antiprotons

To prove the basis of the technique, a small scale moiré deflectometer was realized and tested with a beam of antiprotons with a ~100 keV mean energy [19]. The distance L between the gratings and the detector was set L=25 cm, see Fig.1 for the scheme. The slits in the 100 µm thick silicon grating were manufactured with a 12 µm width and a 40 µm periodicity, ensuring a classical regime when these dimensions are compared to the de Broglie wavelength of the antiprotons. The annihilation position of $\bar{p}$, which have passed the grating, was detected by an emulsion detector [20, 21] with a 2 µm resolution. The moiré deflectometer and the emulsion detector were mounted at the end of the two main magnets (1T and 5T, Fig. 2) in a dedicated vacuum chamber. A moiré pattern of 241 antiprotons annihilation events was recorded and the absolute fringe pattern shift was determined by comparing with a reference Talbot-Laue pattern obtained illuminating the deflectometer with light. The shift is given by $\Delta y = F\tau^2/m$, where F is the force perpendicular to the slits and τ the time of flight between the two gratings, m the $\bar{p}$ mass. The observed upward shift $\Delta y = 9.8$ µm $\pm$ 0.9 µm (stat.) $\pm$ 6.4 µm (syst.) (Fig. 5) was found consistent with a mean force of 530 aN $\pm$ 50 aN (stat.) $\pm$ 350 aN (syst.) acting on antiprotons. This force can be caused by a magnetic field component of ~7.4 G compatible

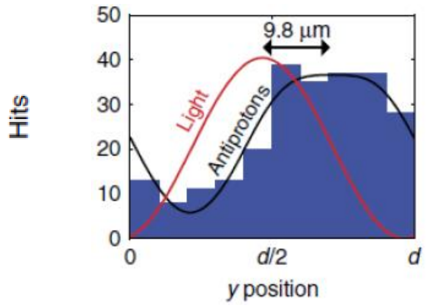

Fig.5 The light and $\bar{p}$ patterns showing the observed $\bar{p}$ shift with the moirè deflectometer

with a magnetic field of ~ 10 G measured in the position of the deflectometer. This experiment proves that the fall under gravity of antihydrogen atoms can be achieved if the small moiré deflectometer is scaled for increasing the time of flight τ. With a shift of the order of 10 µm, a better sensitivity of 11 orders of magnitude can be reached forming a $\bar{H}$ beam with 500 m/s velocity and increasing at 1 m the distance between the two gratings.

6. Conclusions

The last AEgIS experiment achievements in the manipulation of positronium, positrons and antiprotons for the production of an antihydrogen beam and for the study of the free fall of antihydrogen in the Earth's gravitational field have been reported.

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