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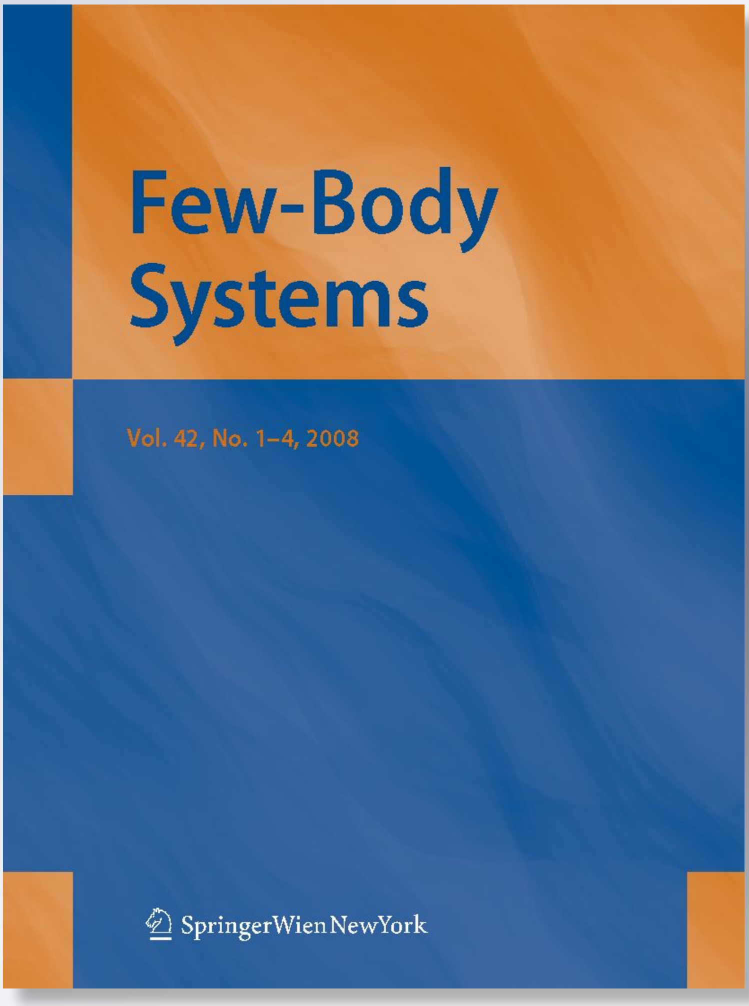

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AEGIS at CERN: Measuring Antihydrogen Fall

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Abstract The main goal of the AEGIS experiment at the CERN Antiproton Decelerator is testing fundamental laws such as the weak equivalence principle (WEP) and the CPT symmetry. In the first phase of AEGIS, a beam of antihydrogen will be formed whose fall in the gravitational field is measured in a Moirè deflectometer; this will constitute the first test of the WEP with antimatter.

1 Introduction

The goal of AEGIS [1] (antimatter experiment: gravity, interferometry, spectroscopy), under construction at CERN, is the study of fundamental physics with antimatter, namely the investigation of the validity of the weak equivalence principle (WEP) and the CPT symmetry. These are important tests of the foundations of both general relativity and modern quantum field theory [2,3].

During the first phase of the experiment, tests of the WEP will be made with antihydrogen produced through the charge-exchange reaction $(Ps)^{*}\overline{p} \rightarrow \overline{H}^{*}e^{-}$. An $\overline{H}$ beam will be formed, whose fall in the gravity field is measured with a Moirè deflectometer. In a second phase of the experiment, antihydrogen will be laser-cooled and confined to perform higher precision g measurements and CPT tests.

The best sensitivity reached up to date for testing the WEP comes from rotating torsion balances [4] and laser lunar ranging (sensitive to Moon and Earth acceleration [5]). They are both in the range of $\sim 10^{-13}$ relative accuracy. While plans exist to significantly improve this sensitivity (http://einstein.stanford.edu/STEP/), there has been no direct measurement of the gravitational acceleration of antimatter up to date.

In this paper we will describe the technique for producing and handling the antihydrogen beam for the gravity measurement as well as the outline of the measurement technique itself.

2 The Production of the Antihydrogen Beam

The measurement of g is performed using the gravitational fall of a beam of antihydrogen. The production of this beam involves the following steps:

- Production of positrons in a Surko-type source and accumulator.
- Accumulation and cooling of antiprotons from the CERN Antiproton Decelerator (AD).
- Production of positronium (Ps) by positron-bombardment of a converter.

The members of AEGIS Collaboration are listed in Appendix.

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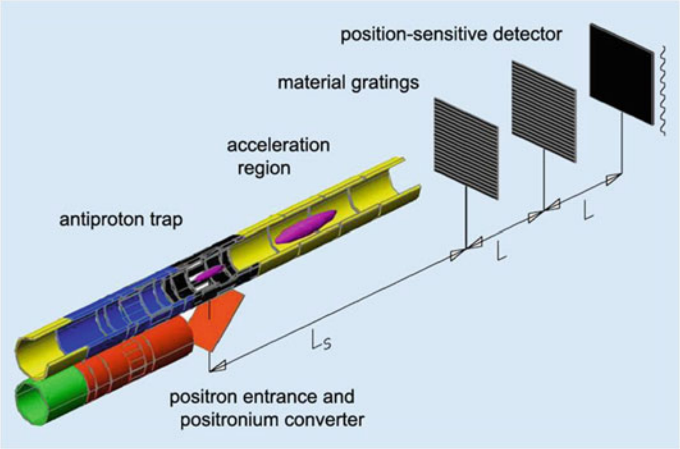

Fig. 1 Sketch of the central part of AEGIS. Two parallel Penning-Malmberg traps ($r = 8$mm) manipulate $\overline{p}$ and $e^{=}$ to form and accelerate $\overline{H}$. They will be mounted inside a 100 mK cryostat in a 1 T magnetic field. The *upper trap* is devoted to antiprotons. Cold $\overline{p}$ wait for Ps in the *black region*. The *lower trap* is devoted to positrons; they will be sent on to the converter to produce Ps. Laser pulses will excite the Ps to Rydberg states to form $\overline{H}$ in the *black region*. The acceleration region shows the bunch of antihydrogen after the Stark acceleration. The two material gratings ($L_s = 50$ cm, $L_s = 30$ cm, transverse dimensions 20×20 cm^2 and the downstream detector are used for the g measurements

- Laser excitation of Ps to an $n \simeq 20$–25 Rydberg state.
- Production of $\overline{H}$ by means of the reaction $(Ps)^*\overline{p} \rightarrow \overline{H}^* e^-$.
- Formation of an antihydrogen beam by Stark acceleration.
- Measurement of g in a Moirè deflectometer.

Antiprotons are coming from the CERN AD, delivering about 3×10^7 particles every 100 s at 5.3 MeV. After an energy degrader, antiprotons are captured and slowed down in a 5 T magnetic field trap configuration located in a cryogenic ultra-high-vacuum environment. After this first trapping, antiprotons are transferred in the *formation region*, conceptually shown in Fig. 1.

The antiprotons are trapped at 4 K in the formation region and further cooled down to ~100 mK (a velocity of about 50 m/s) by means of resistive cooling or sympathetic cooling with laser cooled ions [6].

Once the antiprotons are cooled down to the required temperature, the experimental procedure for producing and accelerating antihydrogen consists of positronium formation and excitation followed by $\overline{H}$ formation and Stark acceleration.

2.1 Positronium Formation and Excitation

Positronium will be formed by an e^+ bunch hitting a suitable converter. The incoming beam of positrons is produced by a Surko-type accumulator delivering a 20 ns bunch of about 10^8 particles with a few (tunable) keV energy.

After Ps has been formed in the bulk of the converter material, ortho-Ps is reemitted out of the target (Fig. 2). Experiments have shown that in suitable converter materials, reemitted Ps in the amount of ~50 % of the impinging e^+ can be obtained [7–10].

The excitation of Ps to Rydberg states is necessary since the cross section of the reaction $(Ps)^*\overline{p} \rightarrow \overline{H}^* e^-$ has a strong dependence on the principal quantum number of the Ps, $\sigma \sim a_0 n^4$ (a_0 being the Bohr radius). Positronium will be laser-excited to high-n Rydberg states ($n \simeq 20$–25) using a $1 \rightarrow 3 \rightarrow n$ excitation scheme [11,12].

2.2 Antihydrogen Formation and Acceleration

Taking into account the production cross section, the geometry of the system and the number of $\overline{p}$ and excited Ps atoms, the aim is to form about 200 antihydrogen atoms per positron shot on the converter. Since this

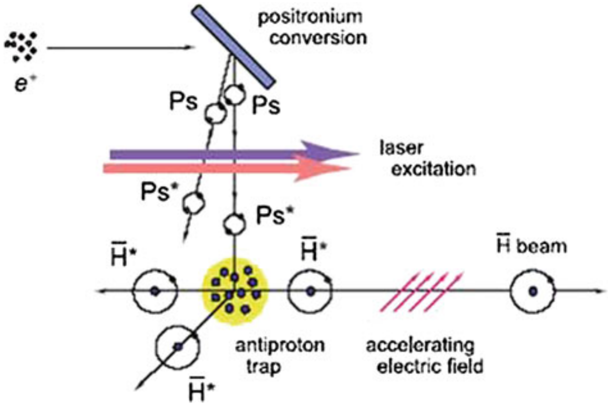

Fig. 2 Schematics of the AEGIS antihydrogen production and acceleration process. The positron bunch lasts about 20 ns while the laser pulse is 10 ns long

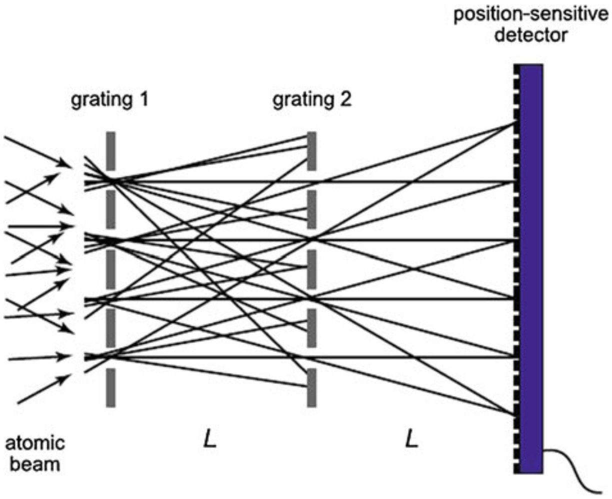

Fig. 3 Principle of the Moirè deflectometer and the detector for AEGIS. L is 30 cm

process follows the accumulation of e^+ in the positron accumulator and the catching, storing and cooling of $\overline{p}$, the averaged antihydrogen production rate will be about 1 Hz. The low temperature of the antiproton cloud allows the production of antihydrogen with an energy of 100 mK, or a thermal speed of 50 m/s (similar to the antiproton energy).

The produced $\overline{H}$ will be Stark-accelerated along the beam axis using a technique recently demonstrated for hydrogen [13]. Following this Stark acceleration process, the $\overline{H}$ atoms will arrive at the beginning of the deflectometer with an axial velocity of 200–500 m/s while preserving a radial velocity spread of 50 m/s.

3 The Gravity Measurement

Measuring g with a flight path of 60 cm as in the design (see Fig. 1) and with a velocity of 500 m/s involves measuring a displacement of $\simeq$20 μm against an 8 mm beam spot. This will be done with a classical Moirè deflectometer; the device [14] consists of three equally spaced and parallel material gratings (Fig. 3). The last plane will be a position-sensitive microstrip detector to register the time and impact point of $\overline{H}$ atoms.

As the atomic beam passes through the gratings, the first two planes select specific propagation directions creating on the third plane a density modulation repeating itself at positions that are integer multiples of the distance between the two first gratings. This technique, originally proposed in [15], can be effectively applied to the case of inertial sensing (and gravity measurements) as discussed in [14].

For the deflectometer to behave like a classical device the following condition has to be satisfied

$$\lambda_{dB} \ll (af)^2 \qquad (1)$$

where λ_{dB} is the de Broglie wavelength of the antiatoms, a is the grating period and f is the opening fraction. In our case, $a \simeq 100$ µm and $f = 0.7$ or $f = 0.3$ so that the above requirement is satisfied for all the velocities of interest. Under these conditions, the system works as a classical deflectometer.

When the antihydrogen beam impinges on the sensitive plane of the device, the modulation intensity pattern will be shifted by a quantity δ that depends on the transit time T, the grating period a and $g : \delta = gT^2/a$. The gravity constant g will be measured by fitting this distribution with the other quantities measured. Taking into account several possible sources of errors, a final 1 % resolution on g can be achieved by launching 10^5 antihydrogen atoms towards the deflectometer. This amount to several months of data taking at the AD.

Appendix

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