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AEGIS at CERN: measuring Antihydrogen fall

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The study of antimatter properties is the main objective of the AEGIS experiment at the CERN Antiproton Decelerator. Antihydrogen and Positronium will be produced to perform tests of fundamental laws, such as the Weak Equivalence Principle (WEP) and the CPT symmetry of Particle Physics. In the first phase of the experiment, a beam of Antihydrogen will be formed whose fall in the gravitational field will be measured in a moiré deflectometer. This will constitute the first high-sensitivity test of the WEP with antimatter. The present paper will review the working principle of the experiment.

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1. Introduction

The goal of the AEGIS (Antimatter Experiment: Gravity, Interferometry, Spectroscopy) [1], under commissioning at CERN, is the study of fundamental physics with antimatter systems, such as the Antihydrogen atom (or matter-antimatter systems such as Positronium). Studies of the Weak Equivalence Principle (WEP) and the CPT symmetry of Particle Physics will be made with Antihydrogen, which will constitute important tests of General Relativity and modern Quantum Field Theory [2,3].

Antimatter is being routinely produced at high energy, mostly in the form of unstable subatomic particles. The first production of a complete neutral antiatom (Antihydrogen, at GeV energies) was made in the '90's at CERN and Fermilab.

Following these pioneering work, the study of neutral antimatter systems at low energy has become possible after the first copious production of cold antiatoms [4,5] at the CERN Antiproton Decelerator (AD) and – more recently – the demonstration of the first Antihydrogen trapping [6].

In the first phase of the AEGIS experiment, a beam of Antihydrogen atoms will be prepared to the goal of measuring its fall in the Earth gravitational field. CPT tests will be performed in a second phase, when trapping of antiatoms and study of $\overline{H}$ atomic transitions will hopefully become possible. Positronium studies will parasitically take place during the overall development of the experimental program. In this paper we will only focus on the gravitational measurement of Antihydrogen as being prepared in the experiment..

The WEP is one of the cornerstones of General Relativity; it states that the trajectory of a falling test body in a gravitational field is independent from the specific body and its composition, while depending only on its initial position and velocity. While the WEP has been very carefully tested for ordinary matter (to the 10^{-13} level) in torsion balance experiments [7], no measurements were possible on the fall of charged antiparticles, due to the overwhelming effect of residual electromagnetic forces [8,9,10]. On the other hand, the only measurement made on a neutral antimatter system so far, only constrains (at the 95% confidence level) the ratio of acceleration g of matter and $\overline{g}$ antimatter to be $-65 < \overline{g}/g < 110$ (see [11]).

Since gravity is the only fundamental interaction which is not explained by a quantum field theory, extensions are considered in view of a possible unification with the other forces. Therefore, while a spin-2 graviton could represent the "ordinary" gravitational interaction, spin-1 (vector) and spin-0 (scalar) carriers are also considered which are not excluded by present precision measurements on matter systems [12]. While indirect arguments have been devised against an anomalous acceleration of antimatter [13], they all rely on theoretical assumptions such as the validity of CPT or the absolute scale of the gravitational potential.

The goal of the first phase of the AEGIS experiment is to address the issue by performing a direct measurement of $\overline{g}$ with a 1% precision, whose relevance is discussed in [14]. This will be done by carefully preparing an Antihydrogen beam and let it fly over some finite distance ($\cong 1 \ m$) to measure the vertical displacement induced by the Earth's gravitational field.

2. The production of the Antihydrogen beam

The production of the antihydrogen beam in AEGIS will be done in pulsed mode by means of the following main steps:

- Accumulation and cooling of antiprotons
- Production and accumulation of positrons in a Surko-type trap system
- Production of Positronium (Ps) by positron-bombardment of a converter
- Laser excitation of the Ps to a $n \cong 25$ Rydberg state
- Production of $\overline{H}$ by means of the reaction $Ps^{*}\ \overline{p} \to \overline{H}^{*}\ e^{-}$
- Formation of an $\overline{H}$ beam by Stark acceleration

The repetition rate of Antihydrogen formation will be of about 200 s. Fig. 1 shows a schematics of the experimental apparatus, located in the CERN AD Hall. The system main components are a positron accumulator and a cryogenic ultra-high vacuum magnetic system featuring superconducting 5 Tesla and 1 Tesla magnets.

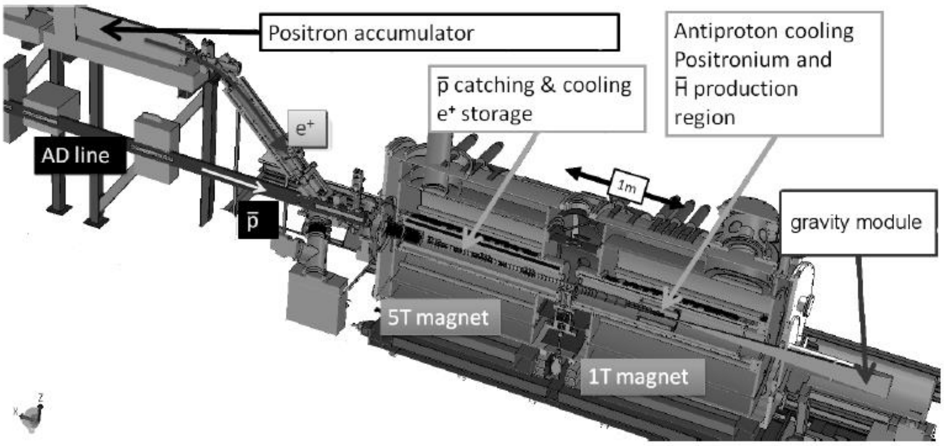

Fig. 1. Artist drawing of the AEGIS apparatus, showing the positron accumulator, the two magnetic systems and the module for the gravity measurement. Antiprotons are coming from the AD (left) and positrons are produced and stored in the positron accumulator.

The AEGIS antihydrogen production scheme will be based on the charge-exchange $Ps^{*}\ \overline{p} \to \overline{H}^{*}\ e^{-}$ production reaction. With respect to other possible production mechanisms (such as radiative recombination or three-body recombination), this proposed reaction offers several advantages. First of all, the cross section scales as $\sigma \approx n^{4}$ (n being the Positronium principal quantum number) and is about $10^{-10}\ cm^{2}$ for $n = 20$. Secondly, the quantum state of the $\overline{H}$ will be (to some extent) related to the Ps excited state and the final temperature of the antiatom will be mostly determined by the temperature of the $\overline{p}$ before the production reaction.

The charge exchange reaction will make use of the two main ingredients of antiprotons and Positronium, separately prepared in the experiment according to the following steps.

2.1 Antiproton preparation

Antiprotons are coming from the AD, delivering about 3×10^7 particles every 200 s with a kinetic energy of 5.3 MeV. After a passive degrader (total thickness $\cong 230\ \mu m$), lower energy $\bar{p}$ are caught in the 5 Tesla cryogenic magnetic field region (fig. 2).

The cold bore of the 5 T magnet contains a trap in the multi-ring geometry with $15\ mm$ electrodes radius. It also contains fast switching electrodes ($9\ kV$) for antiproton catching. The trap is designed for manipulation and cooling of charged particles; a cloud of pre-loaded electrons (roughly, 10^9 particles) can be used to decrease the $\bar{p}$ energy down to the eV range.

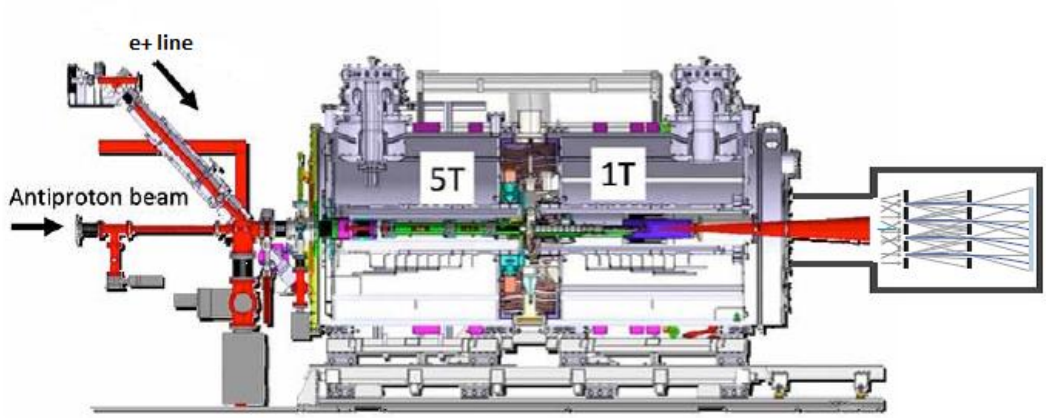

Fig. 2. The two main magnetic systems of the experiment. Antiprotons a from the AD, catched in the 5 T region, are transferred to the 1 T region and then cooled. Positrons coming from the transfer line are injected in the system for antihydrogen formation. Antiatoms are formed in the 1 Tesla region and accelerated towards the moirè deflectometer on the right.

The 5 Tesla system was tested during the first (2012) run. The measured antiproton lifetime was found to be $600\ s$, likely limited by the vacuum level of $8\times10^{-13}\ mbar$.

After catching and manipulation in the 5 T magnet, antiprotons are transferred to the 1 Tesla magnet system which is composed of four electrodes regions with different characteristics (fig. 3). The first part features electrodes with $r = 22\ mm$ used as catching traps for particles coming from the 5 T system. This trap then splits into two smaller radius sections ($5\ mm$ each). The “upper” section is used for positrons (more on this below), while the “lower” on-axis trap – equipped with low noise electronics - is used to store and cool antiprotons down to the lowest possible temperature.

The final cooling of the antiprotons will take advantage of a dilution refrigerator and of a resistive active-feedback cooling system. The final design specifications call for $10^5\ \bar{p}$ cooled down to $\cong 100\ mK$, which corresponds to a velocity of about $50\ m/s$. Sympathetic cooling with (laser cooled) La ions is also being considered for the final stage of the antiproton preparation.

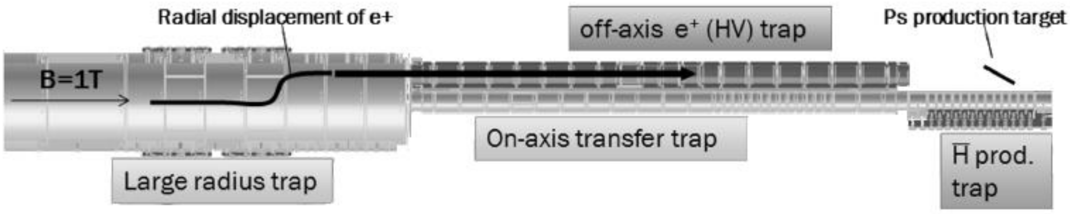

Fig. 3. The trap system of the AEGIS experiment, located inside the 1 Tesla region. The on-axis trap (r= 8 mm) manipulates antiprotons and stores them. Positrons are sent off-axis to reach the production target. The setup is located inside the 1 Tesla magnet, in a vacuum of $\approx 10^{-13}\ mbar$.

2.2 Positron and Positronium production

Positrons are produced in AEGIS by means of a $\cong 50\ mCi$ Na-22 source. A solid rare-gas (Neon) moderator is used together with a Surko-style [15] differentially pumped trap system. The trap system culminates in a positron accumulator (see the top of fig. 1) having the capability of stacking about 10^8 positrons during 200 s. This accumulation time is matched to the antiproton accumulation time discussed above.

Positrons can be directed via an accelerator/buncher to a dedicated chamber for study of Ps spectroscopy (not discussed here) or they can be sent to the main magnets of the experiment, as shown in fig. 2. When positrons are injected in the main trap system (Fig. 3), they can be manipulated, accumulated and and sent off-axis (via the excitation of the diocotron motion [18]) to reach the converter of the experiment.

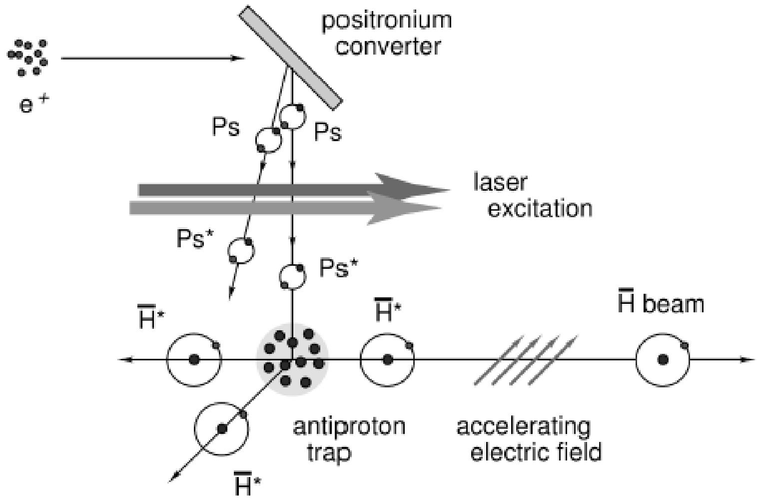

Fig. 3. Schematics of anti-hydrogen production in AEGIS. Positrons hitting the converter will generate Ps which in turn will be laser excited to produce antihydrogen when crossing the antiproton cloud.

Fig. 3 shows the overall scheme of anti-hydrogen formation in AEGIS.

The formation of Positronium with positrons in the 1 T region will be achieved by aiming the positron bunch ($\cong 10\ ns$ long) at suitable converters. The energy of the positrons will be of $5-15\ keV$; Positronium will be produced in the bulk of specially developed porous materials, such as silicon nanochannels [16] (or engineered porous silica [17]). The porous structure of the materials (typically $15\ nm$ width and $1\ \mu m$ depth for the pores) will help thermalizing part of the generated Ps. This will then be used for Antihydrogen production.

In order to increase the cross section for the charge-exchange reaction $Ps^*\ \bar{p} \rightarrow \bar{H}^*\ e^-$, Ps will be excited to a Rydberg level by means of a dedicated laser system, designed according to the $1 \rightarrow 3 \rightarrow n$ excitation scheme. The laser system generates a 205 nm UV pulse and a tunable (1650-1700 nm) IR pulse for excitation on different Rydberg states [19].

3. Measurement of the Antihydrogen fall

In AEGIS, the $\bar{H}$ will be formed in a Rydberg state, with a large electric dipole moment and a high sensitivity to inhomogeneous electric fields. For this reason, the antiatoms will be accelerated by an inhomogeneous time-varying electric field to a velocity of $\approx 500\ m/s$. This Stark acceleration technique has been recently demonstrated for Hydrogen [20] and will allow Antihydrogen to fly to the gravity measurement system. While the formation of antiatoms takes place in a microsecond, the flight time of Antihydrogen in the gravity-measuring module will be of the order of milliseconds. Time of flights can therefore be measured by comparing the response of the gravity detector with respect to the Stark acceleration time.

Measuring $\bar{g}$ with a flight path of about $1\ m$ (as is the case in AEGIS), means measuring a displacement of $\cong 20\ \mu m$ against an $8\ mm$ beam spot. This will be done by using a moiré deflectometer [21] followed by a nuclear emulsion for precision measurement of the Antihydrogen annihilation point (fig. 5). A silicon microstrip detector and a scintillating fiber detector will complete the gravity detector system by providing Time-of-Flight information and pre-identifying the tracks in the emulsion.

The two deflectomer gratings have a pitch a $40\ \mu m$ and a 30% open fraction. In the final detector systems (located also at $50\ cm$ from the second grating) the microstrip detector separates the emulsion volume from the ultrahigh vacuum volume where the deflectometer is located.

As the atomic beam passes through the gratings, the first two planes will select specific propagation directions creating a density modulation repeating itself at positions that are integer multiples of the distance between the first two gratings. Therefore, a periodic fringe pattern is created at the position of the emulsion detector; the vertical position of the fringes depends on the atom velocity and the gravity force acting upon it. The modulation intensity pattern will be shifted by a quantity δ that depends on the transit time T and $\bar{g}$. The gravity constant for antimatter will be then measured by fitting $\delta \approx -\bar{g}T^2$, with the time-of-flight measured on an event-by-event basis by the Time-of-flight detectors and the shift measured by the emulsion.

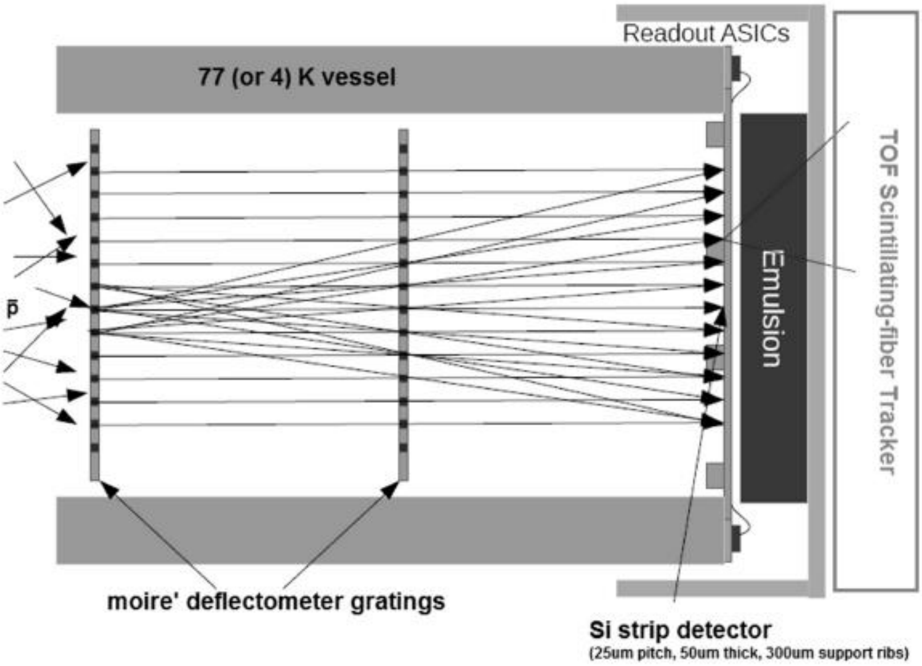

Fig. 5. The moré deflectometer principle and the associated detectors in the gravity measurement module. The horizontal spacing between the gratings is of 50 cm. Note that the moiré interferometer is insensitive to the detailed velocity distribution in the production region (on the left).

In order to validate the use of nuclear emulsions in the frame of the AEGIS experiment, a dedicated run with antiprotons annihilating in the emulsions was made. In this run, the emulsions were made to work in vacuum, using a newly developed emulsion gel. The detector has shown to have a resolution of $1-2\ \mu m$ on the antiproton annihilation point, reconstructed by using the ionizing secondary tracks [22].

Conclusion

The AEGIS experiments consists in a multi-step strategy to test fundamental physics with Antihydrogen (and Positronium). The experiment was approved in 2008 and is now in an advanced stage of construction, commissioning and preliminary test of subsystems. Preliminary measurements have been made concerning antiproton annihilation in emulsion and silicon detectors [21, 22] as well as tests of the principle and resolution of the moiré deflectometer and the emulsions [23]. The next steps ahead are the spectroscopic study of Positronium, the formation of Antihydrogen and the measurement of $\overline{g}$ with 1% sensitivity.

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