THE WEAK EQUIVALENCE PRINCIPLE WITH ANTIMATTER: THE AEgIS EXPERIMENT AT CERN

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The AEgIS experiment at CERN's Antiproton Decelerator (AD) aims at performing a direct measurement of the gravitational force on antimatter to probe the Weak Equivalence Principle of General Relativity with antimatter. The idea is to measure the vertical displacement of a cold antihydrogen beam, due to the gravitational force, by using a moiré deflectometer. Antihydrogen will be formed through the reaction of charge exchange between cold antiprotons and Rydberg positronium. An overview of the physics goals, experimental setup and preliminary results is presented.

1 Introduction

Since the XVI century, it is experimentally known that objects fall in the gravitational field of the Earth with the same acceleration, regardless their mass or composition. This led Newton to conclude, in his *Philosophiae Naturalis Principia Mathematica* [1], that inertial and gravitational mass must be necessarly equivalent. Today this equivalence is know as *Weak Equivalence Principle* (WEP). In 1916 Einstein formulated a *stronger* version of the WEP [2], the *Einstein Equivalence Principle* (EEP), which is not only a pillar of General Relativity but, more in general, of all metric theories of gravity[3]. The WEP is a necessary condition for the EEP and it has been widely tested experimentally, resulting in very stringent limits on its possible violation with *ordinary* matter [3].

At present, several experimental and theoretical arguments seem to suggest that the WEP should also hold for antimatter [5,6,7]. However, not only all these arguments are indirect and rely on some theoretical assumptions, but, on the other hand, most of the attempts for a quantum theory of gravity tipically predict interactions which could violate the WEP for antimatter[8].

The AEgIS experiment aims at performing a direct test of the WEP on antimatter by measuring the acceleration g of a cold beam of antihydrogen in the Earth's gravitational field. The idea is to measure the vertical displacement, due to gravity, of a beam of antihydrogen crossing a moiré deflectometer coupled to a position sensitive detector (see Section 2). The goal is to reach a precision of the order of some percent on g. In the following section an overview of the AEgIS experiment is given.

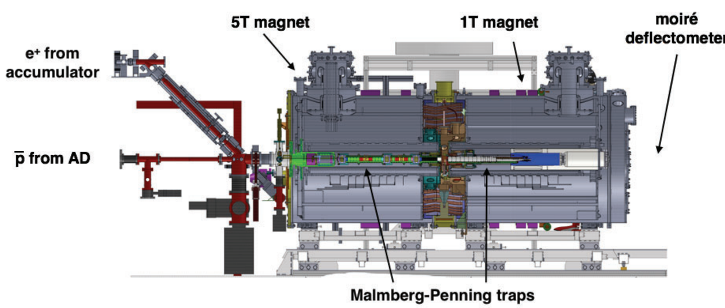

Figure 1 – Scheme of the experimental setup of the AEgIS experiment (moiré deflectometer not reported).

2 Overview of the AEgIS experiment

The AEgIS apparatus is schematically shown in Fig. 1 and consists of a 5 T and a 1 T superconducting solenoids, which house a Malmberg-Penning trap each [9]. The CERN's *Antiproton Decelerator* provides AEgIS with bunches of $\sim 3\times10^7$ antiproton, with 5 MeV of kinetic energy, every ∼100 s. The antiprotons loose their energy down to few keV by crossing a set of thin aluminum foils (degrader) and a fraction of them are caught by the trap in the 5 T magnet. They are then cooled to few K with sympathetic electron cooling and transferred to the 1 T trap for the $\bar{H}$ production. Rydberg antihydrogen atoms $\bar{H}^*$ will be produced from cold $\bar{p}$ and Rydberg ortho-positronium Ps^* via by the so-called *charge-exchange process* [10] $Ps^* + \bar{p} \rightarrow \bar{H}^* + e^-$, which is sketched in Fig. 2a . The positronimum is produced by sending pulses of positrons, emitted by a Na^{22} source and bunched in a Surko-type accumulator, toward a nanoporous silica target and exciting the emerging positronium to Rydberg states by two laser pulses. The charge-exchange process allows the production of ultra cold Rydberg $\bar{H}$ atoms, which, thanks to their large electric dipole moment, can be accelerated by electric field gradients to form a beam.

The beam of $\bar{H}$ atoms passes through the so-called *gravity module*, which is composed by a classical moiré deflectometer [11] with two gratings, coupled to a position sensitive detector, as shown in Fig. 2b. For simple geometrical arguments, as the beam crosses the gratings it produces a fringe patter on the sensitive detector. Because of the gravity, this pattern is vertically shifted with respect to the one produced using light (Fig. 2b). This vertical displacement h is:

$$h = g_{\bar{H}} \left(\frac{L}{v} \right)^2, \tag{1}$$

where $g_{\bar{H}}$ is the modulus of the gravitational acceleration experienced by the $\bar{H}$ atoms, v is component of their velocity along the direction perpendicular to the grating period, and L is the distance between gratings. As Eq. 1 shows, this strategy allows a direct measurement of $g_{\bar{H}}$, with a resolution which mainly depends on the number of reconstructed $\bar{H}$ atoms and the detector resolution.

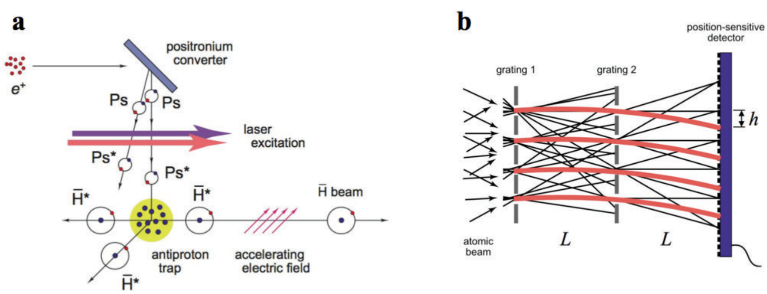

Figure 2 – a) Scheme of the Rydberg antihydrogen production via charge-exchange in AEgIS; b) Scheme of the AEgIS gravity module.

3 First results with a small-scale Moiré deflectometer

A proof of principle of the measurement technique has been performed [12] by exposing a small-scale moiré deflectometer ($L = 25$ mm), coupled to an emulsion detector, to a beam of antiprotons coming from AD, whose energy at the gravity module was estimated to be ~ 0.1 MeV from MC simulations. The sensitive detector was composed by two different regions, as shown in Fig. 3a: one with only the emulsion, and one with an additional grating in direct contact to it. The goal of the contact grating was to align the measurements with antiprotons and visible light, being the latter used to create the reference frame.

A total of 241 annihilation stars were recorded on the nuclear emulsions. Their positions were reconstructed, with an accuracy of $\sim$2 μm, and then compared to the reference light pattern. Fig. 3b shows the reconstruction of the annihilation vertexes from data (blue dots), superimposed to the reference pattern (red band), as produced without (left) and with (right) the contact grating. The periodicity of data was extracted using a Rayleigh test and the y-coordinates of the reconstructed vertexes were compared (in grating units d) to what expected from the reference frame, as shown in Fig. 3c. The period of the moiré pattern of the $\bar{p}$ beam was found to be the same as the reference light pattern, shifted by $9.8 \pm 0.9(stat) \pm 6.4(syst)$ μm. The observed shift of the moiré pattern is consistent with a mean force acting on the antiprotons of $530 \pm 50(stat) \pm 350(syst)$ aN. This force can be explained in terms of the Lorentz force of a 7.4 G magnetic field, consistent with the residual magnetic field of $\sim$10 G measured at the location of the moiré deflectometer. Although a measurement of the gravitational force on the antiprotons cannot be inferred from data, the results prove that the use of a moiré deflectometer, coupled to a position detector, allows the measurement of a micrometric phase shift due to a magnetic force. Moreover, according to Eq. 1, this measured phase shift is expected to be comparable to the one to be produced by the gravitational force on antihydrogen, in the full-scale deflectometer ($L = 1$ m) and with $v \sim 500\ ms^{-1}$.

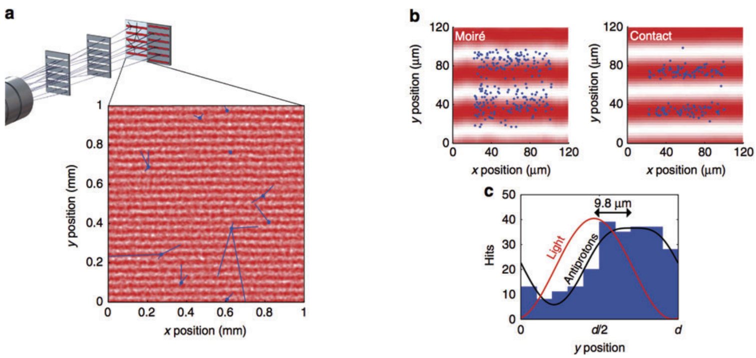

Figure 3 – a) Schema of the small-scale gravity module used [12]; b) Shadow fringe pattern on the emulsion detector produced by the moiré deflectometer (left) and the contact grating (right) [12]; c) Vertical displacement of the $\bar{p}$ fringe with the respect to reference one created with light (in grating units d) [12].

4 Conclusions

The main goal of the AEgIS experiment is to probe the WEP with antimatter, by measuring the gravitational acceleration of a $\bar{H}^*$ beam with an accuracy of some percents. The experimental setup is almost fully in place, with the exception of the full-scale gravity module, which is still under development. A proof of principle has been performed, using a small-scale prototype of the moiré deflectometer and a beam of antiprotons. The results showed that a micrometric shift is observable, proving the feasibility of the proposed detection method. At present, the $\bar{H}^*$ production is expected to be achieved by the end of this year, while the first measurement of $g_{\bar{H}}$ is planned for the following years.

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