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The AEGIS experiment at CERN

Measuring the free fall of antihydrogen

The AEGIS Collaboration

Abstract After the first production of cold antihydrogen by the ATHENA and ATRAP experiments ten years ago, new second-generation experiments are aimed at measuring the fundamental properties of this anti-atom. The goal of AEGIS (Antimatter Experiment: Gravity, Interferometry, Spectroscopy) is to test the weak equivalence principle by studying the gravitational interaction between matter and antimatter with a pulsed, cold antihydrogen beam. The experiment is currently being assembled at CERN's Antiproton Decelerator. In AEGIS, antihydrogen will be produced by charge exchange of cold antiprotons with positronium excited to a high Rydberg state ($n > 20$). An antihydrogen beam will be produced by controlled acceleration in an electric-field gradient (Stark acceleration). The deflection of the horizontal beam due to its free fall in the gravitational field of the earth will be measured with a moiré deflectometer. Initially, the gravitational acceleration will be determined to a precision of 1%, requiring the detection of about 10^5 antihydrogen atoms. In this paper, after a general description, the present status of the experiment will be reviewed.

Keywords Antimatter · Antihydrogen · Gravity · Matter interferometry · Deflectometry · Weak equivalence principle

1 Introduction

Gravity takes a special place amongst the four fundamental interactions. While the electromagnetic force and the strong and weak nuclear forces are described by quantum field theories, general relativity expresses gravity as a geometric phenomenon: Test bodies travel along geodesics in four-dimensional spacetime, which is

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distorted by the presence of massive objects. It follows directly from this geometric approach to gravity that all bodies must behave in exactly the same way in an external gravitational field, regardless of their composition. This postulate is called the weak equivalence principle (WEP) of general relativity. It has been extremely well tested with ordinary matter, at a wide range of length scales from microscopic to astronomical distances [1].

Attempts have been made to formulate a quantum theory of gravity in order to construct a more consistent theoretical framework for all forces, ultimately providing a "Theory of Everything" combining all four interactions. In quantum gravity, the attraction (or repulsion) between two bodies is due to the exchange of virtual bosons, called gravitons, coupling to a gravitational charge. The properties of the force depend on the spins and masses of the exchange bosons as well as the signs of the charges. As a general feature of quantum field theories, the exchange of even-spin particles creates an attractive force between all types of charges, whereas odd-spin particles mediate a repulsive force between like charges.

Ordinary "Newtonian" gravity corresponds to the exchange of massless tensor (spin-2) gravitons. Additionally, vector (spin-1) and scalar (spin-0) gravitons may exist. A hypothetical vector graviton would result in a repulsive force between like charges, producing an opposite effect on matter and antimatter particles—a violation of the WEP. Assuming similar masses and strengths of the vector and scalar components, their effects could cancel out in ordinary matter. They would, however, produce a deviation from Newtonian gravity in the gravitational interaction between matter and antimatter. Such an anomalous "anti-gravity" could result in the segregation of matter and antimatter in different regions of the cosmos and hence explain the apparent absence of antimatter in the observable universe [2].

The effect of gravity on antimatter has never been tested experimentally. Two previous attempts, with positrons [3] and antiprotons [4], were unsuccessful due to the overwhelming effect of stray electromagnetic fields on the charged test particles. Hence, an anomalous gravitational acceleration of antimatter cannot currently be ruled out. Ever since the first production of cold neutral antihydrogen atoms at CERN [5, 6], a high-precision test of antimatter gravity has come within reach. It is the main physics goal of the AEGIS experiment (Antimatter Experiment: Gravity, Interferometry, Spectroscopy), currently being set up at CERN, to measure the effect of gravity on antimatter for the first time [7, 8].

2 Experimental technique

The AEGIS experiment is located at CERN's Antiproton Decelerator (AD) [9]. Its main principle is a measurement of the vertical deflection of a pulsed, cold, horizontal antihydrogen ($\overline{\mathrm{H}}$) beam in the gravitational field of the earth. $\overline{\mathrm{H}}$ will be produced by a charge exchange reaction between highly excited positronium (Ps) and an ensemble of ultracold antiprotons ($\bar{p}$). The design of the apparatus draws heavily on the experience gained with other $\overline{\mathrm{H}}$ experiments, in particular, techniques developed for the capture and cooling of $\bar{p}$ and positrons (e^+) in Penning traps. The experimental procedure consists of three main steps, which will be reviewed in the following sections. An overview sketch of the low-magnetic-field part of the AEGIS apparatus, including the gravimeter, is shown in Fig. 1.

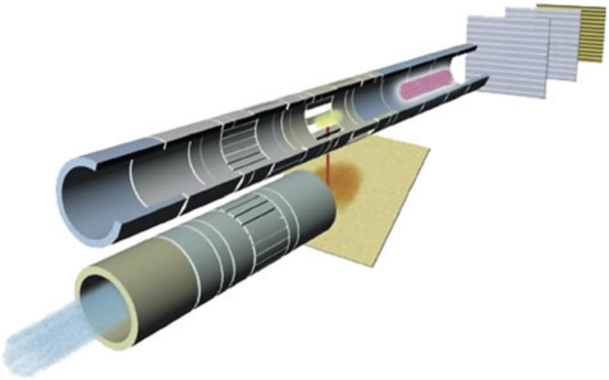

Fig. 1 Three-dimensional cut-open sketch of part of the AEGIS apparatus, showing the low-field Penning traps, the positronium converter, and the deflectometer. Illustration by Internosei, used with permission © Asimmetrie/INFN

2.1 Positronium production and excitation

In the AEGIS experiment, Ps will be produced by implanting e^+ at kinetic energies of several keV into a wafer of nanoporous insulator, which acts as a highly efficient Ps converter [10]. The e^+ scatter off atoms and electrons (e^-) in the bulk and are slowed to eV energies within a few ps. The slow e^+ capture either bound e^- or those released in prior collisions and form Ps. These tend to accumulate in pores of the material due to the reduced dielectric strength. Ps repeatedly bounces off the cavity walls in the pores and is gradually thermalized with the target material. Despite some *ortho*-Ps losses due to so-called pick-off annihilations of e^+ on the cavity walls, a large fraction diffuses out of the film at thermal energies.

Overall, the *ortho*-Ps fraction released from the sample can exceed 20% in silica-based materials cooled to 50 K, as demonstrated by 2–3 gamma ratio of positronium (3γ PAS) measurements [11]. The exact yield and the final velocity distribution depend on the characteristics of the target material, the implantation depth, and the target temperature. Furthermore, it was demonstrated that the energy profile of Ps emitted from the surface of a silica film at room temperature followed a Maxwell–Boltzmann distribution, indicating that a large fraction of the Ps was fully thermalized [12]. Members of the AEGIS Collaboration have been investigating the optimal parameters of a new converter material and the most favorable e^+ energy in terms of *ortho*-Ps yield and temperature, both theoretically and experimentally [13, 14].

The Ps cloud exiting the sample must be excited to Rydberg levels. Laser systems for direct photo-excitation (≈ 180 nm) are not commercially available, hence we will perform a two-step excitation, from the ground to the $n = 3$ state ($\lambda = 205$ nm), and then to a suitable high-n level band ($\lambda \approx 1670$ nm) [15]. The development of the two pulsed laser systems, both based on optical parametric generator crystals with amplification stages and pumped by a Q-switched Nd:YAG laser, has recently been completed [16]. The lasers provide sufficient power to excite the Ps within a few ns. Their bandwidths are tailored to the widths of the transitions, which are broadened by the Doppler effect as well as by level splitting due to the motional Stark and Zeeman effects.

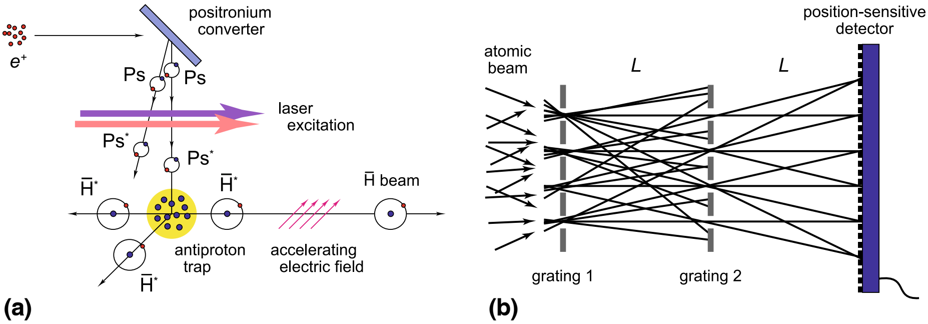

Fig. 2 **a** Method used for $\overline{\mathrm{H}}$ recombination and subsequent acceleration. **b** Principle sketch of the moiré deflectometry technique with two identical gratings and a position-sensitive detector

2.2 Antihydrogen recombination and beam formation

AEGIS will employ an $\overline{\mathrm{H}}$ recombination scheme based on resonant charge exchange with Ps according to the reaction [17]

$$\mathrm{Ps}^* + \bar{p} \longrightarrow \overline{\mathrm{H}}^* + e^-, \tag{1}$$

where stars denote highly excited Rydberg states. The principle is illustrated in Fig. 2a. This reaction has a particularly large cross-section, which scales approximately with the fourth power of the principal quantum number. Most importantly, $\overline{\mathrm{H}}$ formed with $\bar{p}$ at rest is created with a velocity distribution dominated by the $\bar{p}$ temperature, hence the surrounding (cryogenic) environment. A conceptually similar charge exchange technique based on Rydberg cesium [18] has been successfully demonstrated several years ago [19].

The created anti-atoms, produced at velocities of $25\ldots80\ \mathrm{m\,s^{-1}}$, will be axially accelerated by exposing them to an electric-field gradient (Stark acceleration). Since the dipole moment scales approximately with the square of the principal quantum number, Rydberg atoms are especially amenable to being manipulated in this way. One of the member groups of AEGIS has recently demonstrated the Stark acceleration of Rydberg hydrogen [20, 21], achieving accelerations of $2 \times 10^8\ \mathrm{m\,s^{-2}}$. In this way, a horizontal beam of $\overline{\mathrm{H}}$ atoms at a velocity of $\approx 400\ \mathrm{m\,s^{-1}}$ will be projected toward the gravimeter.

2.3 Gravity measurement and data analysis

In the AEGIS experiment, the deflection of the horizontal $\overline{\mathrm{H}}$ beam will be measured with a moiré deflectometer, the classical counterpart of a matter wave interferometer [22, 23]. Three identical material gratings are placed at equal distances L from each other. A particle beam passing through the first two gratings produces a shadow pattern on the third. The change in vertical position of the shadow pattern due to gravity is determined by recording the overall transmission as a function of the position of the third grating. Alternatively, a position-sensitive detector may be used to replace the third grating and detector, as shown in Fig. 2b. A three-grating moiré deflectometer was first used by one of the AEGIS members to measure the local gravitational acceleration to a relative precision of 2×10^{-4} [24].

Under the influence of gravity, the shadow pattern is vertically displaced by a distance

$$\delta x = -gT^2, \tag{2}$$

where g is the local gravitational acceleration and $T = L/v$ is the time of flight between each pair of gratings of a particle beam traveling at velocity v. To extract the value of g from the primary observables (time of flight T and vertical displacement of the fringe pattern δx) the $\overline{\mathrm{H}}$ annihilation events are first binned in symmetric classes of T^2. Secondly, the vertical displacement δx of the fringe pattern is extracted for each of the count classes. Finally, the vertical displacement for all count classes is plotted against the mean time of flight in the class. A quadratic fit to that graph will then yield g. The zero position of the vertical displacement (i.e., without gravity) can be obtained by performing a calibration measurement with the gratings and detector rotated by 90° about the beam axis.

3 Current status and outlook

As of the end of 2011, installation of the AEGIS apparatus at the AD is well advanced. The e^+ source, rare-gas moderator and e^+ trap have been installed, as well as the high-field superconducting magnet and $\bar{p}$ trap. The low-field superconducting magnet has been completed and is awaiting installation. The e^+ accumulator, the dilution refrigerator, and the detector monitoring $\overline{\mathrm{H}}$ production will be installed in the first half of 2012. Finally, the recombination traps, the moiré deflectometer and the position-sensitive detector are currently under development. The system is expected to be ready for $\bar{p}$ capture in 2012 and for a first gravity measurement in 2014, after the CERN accelerator shutdown scheduled for 2013.

Initially, it is planned to measure g of $\overline{\mathrm{H}}$ to a relative precision of 1%, based on the cooling of $\bar{p}$ to $T = 100$ mK with a dilution cryostat. Monte Carlo simulations performed by us indicate that this will require about 10^5 $\overline{\mathrm{H}}$ atoms, corresponding to about 2–3 weeks of data taking. At a later stage of the experiment, we intend to significantly improve the relative precision by cooling the $\bar{p}$ to ultracold temperatures by evaporative cooling or indirect laser cooling. In summary, the AEGIS experiment, currently being set up at the CERN AD, is en route to performing the first measurement of the gravitational interaction of antimatter.

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