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Article

The Effect of Gravity on Antimatter: The ALPHA Experiment †

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Abstract: Although the gravitational interaction between matter and antimatter has been the subject of theoretical speculation since the discovery of the latter in 1928, only recently was the ALPHA experiment at CERN able to observe, for the first time, the effects of gravity on antimatter atoms, namely on antihydrogen. After an introduction of the concept of antimatter, along with its still-unresolved mysteries, details about how antihydrogen is produced at the Antimatter Factory at CERN will be given. Finally, the measurement of the acceleration of gravity of antihydrogen atoms falling in the Earth's gravitational field will be described.

Keywords: antimatter; gravity; antihydrogen; acceleration of gravity

1. Introduction

Over the last century, the General Theory of Relativity has passed a number of stringent experimental tests [1]. Among its core tenets, and which is still experimentally unchallenged, is the Einstein equivalence principle (EEP). The EEP, in its modern form [2], consists of three parts: the universality of free fall, also known as the weak equivalence principle (WEP); the local Lorentz invariance (LLI); and the local position invariance (LPI). The WEP implies that all objects, under the sole influence of gravity, fall at the same rate, regardless of their internal composition or structure. General Relativity was introduced in 1915, while antimatter was discovered about 15 years later. Does the WEP hold for antimatter too? In effect, there was always a general consensus that also antimatter should behave, gravitationally, in the same way as matter. In other words, the WEP is widely expected to hold for antimatter. Nevertheless, a violation is not a priori excluded and, more importantly, no direct measurement was available. Indeed, attempts for a quantum theory of gravity typically result in new interactions which may violate the WEP. See, for example, the Kaluza–Klein theory [3]. In addition, a subset of the gravitationally coupled minimal SME (Standard Model Extension) envisages mechanisms to break CPT and Lorentz invariance with consequences also on the gravitational behaviour of antimatter [4]. In summary, there are theoretical scenarios in which matter and antimatter may behave in a different way under the same gravitational field. Physicists have obviously tried to experimentally verify the influence of the Earth's gravitational field on antimatter, specifically on charged antiparticles, but this has been unsuccessful. In particular, in 1967, Fairbank and Witteborn tried to use positrons [5], while in 1989 the PS-200 experiment at CERN employed antiprotons [6,7]. The reason for the impossibility of testing gravity on charged antiparticles is to be found in the stray E and B fields whose forces are an order of magnitude higher than the gravitational one. It was clear, at the point, that the best way to approach, experimentally,

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the question of gravity on antimatter was through an antimatter neutral system. This was possible thanks to the construction at CERN, at the end of the previous millennium, of the Antimatter Factory, a complex composed of an Antiproton Decelerator (AD) [8] and, recently, by an ELENA [9] ring (The Extra Low ENergy Antiproton became operational in 2018). Just a few years later, in 2002, the Athena experiment was able to produce the first antihydrogen atoms in an electromagnetic trap [10]. In the last two decades, various experiments, namely AEgIS [11], ALPHA and GBAR [12], pursued the measurement of the gravitational interaction of antihydrogen with the Earth's field. Finally, in 2023, the ALPHA collaboration was able to obtain the first result [13], which will be described here below.

2. The ALPHA Experiment

ALPHA (Antihydrogen Laser Physics Apparatus) is an international collaboration comprising 17 institutions and approximately 50 scientists. Its goal is the precision measurement of the properties of atomic antihydrogen and their comparison with those of hydrogen, for experimental tests of the Charge–Parity–Time (CPT) symmetry and of the weak equivalence principle. The antihydrogen is produced in the experiment by combining antiprotons from the Antiproton Decelerator (plus ELENA) and positrons from a Na-22 source and a positron accumulator. The production scheme relies on the well-established three-body recombination process [14]. The positively and negatively charged particle plasmas are manipulated in (nested) Penning–Malmberg traps, while Ioffe–Pritchard traps are used to confine the produced neutral antihydrogen. The Penning and Ioffe traps overlap in the antihydrogen production regions. High production yields and long confinement times of cold antihydrogen atoms, necessary for the precision measurements of its properties, are routinely achieved [15].

As summarized in Figure 1, two measurement sectors are present: a horizontal one primarily dedicated to optical spectroscopy measurements (ALPHA-2 in its present status), and a vertical one primarily devoted to gravitational and hyperfine spectroscopy measurements (ALPHA-g). A cross section of the ALPHA-g apparatus, showing the trap system, the magnets, the cryogenics and the detectors, is shown in greater detail in Figure 2.

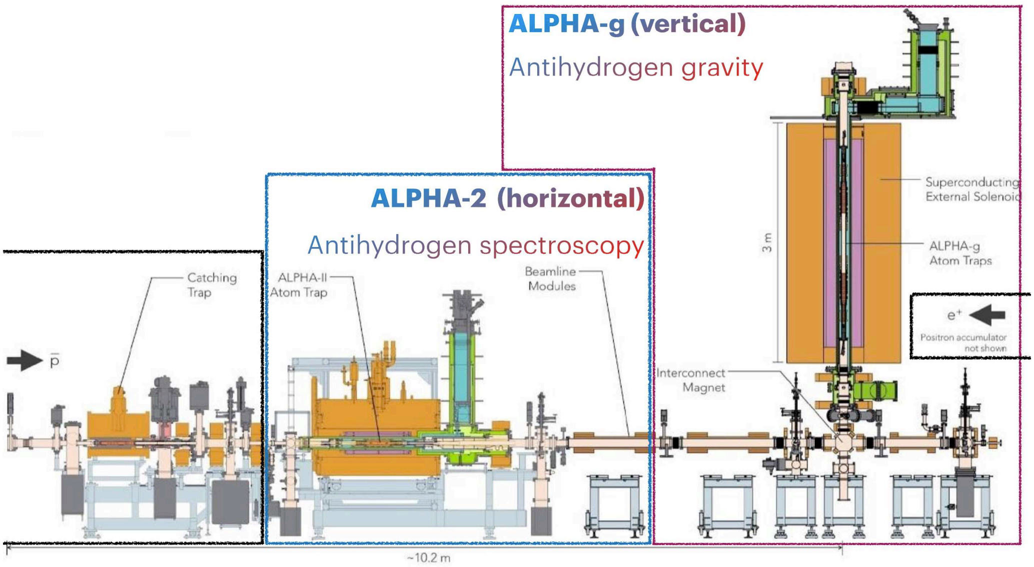

Figure 1. A schematic overview of the ALPHA experimental apparatus. The antiprotons are coming from the left, delivered by AD/ELENA, while the positrons are coming from the right, from the ALPHA positron accumulator (not shown here). Beside the catching trap region, which is shared, two different regions can be highlighted. The horizontal one, called ALPHA-2, is for studies of antihydrogen spectroscopy and the vertical one, named ALPHA-g, was mainly developed for the study of gravity.

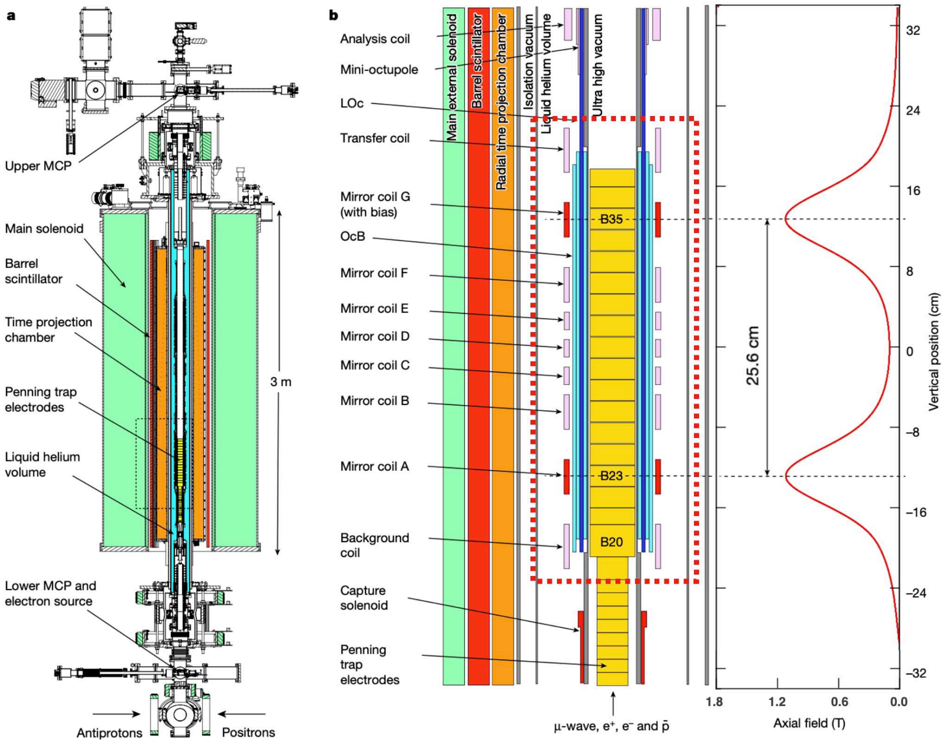

Figure 2. (**a**) Cross section of the ALPHA-g apparatus, showing the trap system, the magnets, the cryogenics and the detectors. (**b**) Expanded view of the bottom antihydrogen trap, delimited in (**a**) by the dashed rectangle, used for the measurement presented here. The red rectangle in (**b**) is delimiting the electromagnetic trap region where the measurement took place. The on-axis axial field profile, at full current, is shown on the right. See text and [13] for details.

3. The Experimental Method

The experimental protocol was to stack antihydrogen atoms, then release them by simultaneously ramping down the current in two mirror coils, specifically mirror coil A and mirror coil G in Figure 2, over 20 s (fast ramp) or 130 s (slow ramp). The anti-atoms could escape either to the top of the trap, through mirror G, or the bottom, through mirror A, and subsequently be annihilated on the walls of the apparatus. The annihilations and their positions (vertices) could be detected and reconstructed.

If hydrogen atoms were trapped under ALPHA-g conditions and gradually released from a vertically symmetric trap (i.e., with the on-axis magnetic field maxima of mirror A and mirror G at the same value, $B_A = B_G$), about 80% of them would exit through the bottom. The asymmetry is clearly due to the downward force of gravity. The remaining 20% of the sample could, anyhow, escape upward, since the anti-atoms would not be standing still but moving with a given energy (velocity) distribution corresponding to the trap depth, equivalent to a temperature of 0.5 K. The goal of the current experiment was to test this behaviour for antihydrogen. Vertical gradients in the magnetic field magnitude can obviously mimic the effect of gravity. Quantitatively, the local acceleration of gravity, g, which is about 9.81 $\mathrm{m/s^2}$, is equivalent to a vertical magnetic field gradient of 1.77×10^{-3} T/m acting on a hydrogen atom in the ground state. The peaks in the mirror coil axial field strength are separated by 25.6 cm (see Figure 2) at full current, so a field difference of 4.53×10^{-4} T between these points would mimic gravity. The actual experiment involved many trials of antihydrogen accumulation and release for various magnetic *bias* levels. We define the imposed bias as

$$\frac{\mu_B(B_G - B_A)}{m_H(z_G - z_A)} \tag{1}$$

where μ_B is the Bohr magneton, $(B_G - B_A)$ is the difference between the on-axis field maxima under the two mirror coils, m_H is the hydrogen gravitational mass and $(z_G - z_A)$ is the height difference between the positions of the on-axis field maxima. It is convenient to express the bias relative to g. Thus, in a one-dimensional model, a magnetic bias of -1 g would effectively balance the downwards gravitational force for hydrogen. Having assumed no a priori direction or magnitude for the gravitational force on antihydrogen, we investigated nominal bias values of ± 10 g, ± 3 g, ± 2 g, ± 1.5 g, $\pm$ 1 g, ± 0.5 g and 0 g. For more details about the experimental method, see [13]. It is worth mentioning here that the full ALPHA-g apparatus comprises three antihydrogen trapping regions; only the bottom one (dashed rectangle in Figure 2a) was employed for this measurement, since the other regions were not instrumented yet.

4. Results

The measurement of gravity on antihydrogen was obtained from the fast ramp, for which all the biases data, listed above, were collected. All the details are reported in [13]. To illustrate the physical meaning of the results here, below, the raw event z-distributions for the slow ramp release are shown in Figure 3 along with a schematic representation of the vertical B field in the region of the trapped antihydrogen. Qualitatively, the experimental data in Figure 3 exhibit the behaviour characteristic of gravitational attraction between antihydrogen and the Earth. At a bias of about 0 g, the anti-atoms exit predominantly at the bottom of the trap, while at a bias of -2.0 g the antihydrogen atoms escape mainly from the top. The balance point is close to -1 g, as naively expected from the simplified one-dimensional argument in which a B-field difference of about 4.5 G between mirror G and mirror A, along the centre of the trap, is able to compensate the effect of gravity. On the other hand, to extract the value of the acceleration of gravity from such distributions is not an easy task. The B field is not perfectly uniform in the trap, since it changes when moving, both axially and radially, from the trap centre. In other words, when travelling inside the trap well, antihydrogen atoms experience different B fields (different magnetic forces), while experiencing the same gravitational force. To extract the value of the gravitational acceleration, a detailed and complex simulation of the ALPHA magnetic trap and of the antihydrogen dynamics was needed. The simulations have been produced for various hypothetical values of acceleration of gravity of antihydrogen (between −1 g and + 1 g). A comparison of the data with the simulation allowed for the measurement of the gravitational acceleration of the antihydrogen. Considering g = 9.81 m/s^2, it resulted in a value equal to 0.75 ± 0.13 (statistical + systematic) $\pm$ 0.16 (simulation)) g. The value was extracted choosing the "best fit" between simulations and data. The statistical uncertainty and the systematic uncertainty were summed in quadrature (with the statistical uncertainty, due to counting statistics, being 0.06 g). The main source of systematic uncertainty was connected to the detector efficiency difference in measuring antihydrogen exiting from the bottom and from the top of the trap. The simulation uncertainty was an estimate of the potential impact of various unmeasured quantities, such as magnet winding misalignments,

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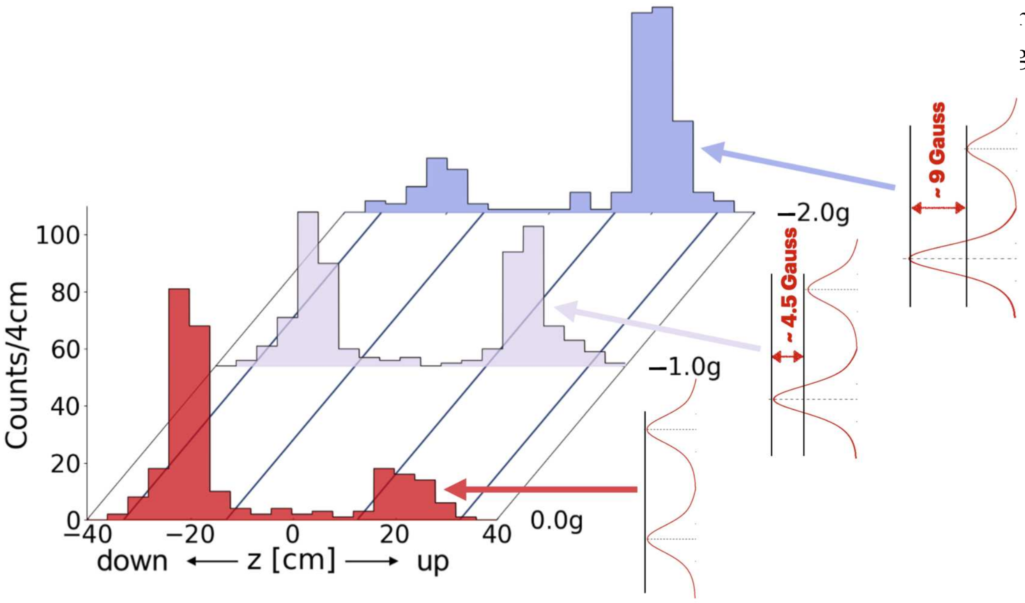

Figure 3. The raw event z-distributions are displayed as histograms for each of the bias values for the 130 s slow ramp. These are uncorrected for background or detector relative efficiency. The three different biases, defined as ($B_G - B_A$) configurations, are schematically represented in the figure.

5. Conclusions

The effect of gravity on atoms of antihydrogen has been observed for the first time. From the obtained result, the dynamic behaviour is consistent with the existence of an attractive gravitational force between these atoms and the Earth. The existence of repulsive gravity of magnitude 1 g between the Earth and antihydrogen can be ruled out. The results are thus far in conformity with the predictions of General Relativity. Nevertheless, theoretical scenarios in which gravity is only slightly different between matter and antimatter cannot be completely ruled out ([16]). Having determined the sign and approximate magnitude of the acceleration, our next challenge, in the coming years, is to extend the method to measure the magnitude as precisely as possible, to provide a more stringent test of the WEP. Colder atoms will obviously allow for more sensitive measurements. Our simulations indicate that colder antihydrogen atoms that will steepen the transition region of the escape curve, coupled to a better control of the magnetic fields, will be possible in the central trapping region of the ALPHA-g apparatus. The central trapping region of ALPHA-g, not yet utilized, is indeed designed to be less susceptible to unprogrammed magnetic fields and to work with colder atoms. Both improvements will allow for higher-precision measurement in the coming years.

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