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GBAR

Gravitational behavior of antihydrogen at rest

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Abstract The GBAR project aims to perform the first test of the Equivalence Principle with antimatter by measuring the free fall of ultra-cold antihydrogen atoms. The objective is to measure the gravitational acceleration to better than a percent in a first stage, with a long term perspective to reach a much higher precision using gravitational quantum states of antihydrogen. The production of $\sim$20 μK atoms proceeds via sympathetic cooling of $\overline{H}^{+}$ ions by Be^{+} ions. $\overline{H}^{+}$ ions are produced via a two-step process, involving the interaction of bursts of 10^7 slow antiprotons from the AD (or ELENA upgrade) at CERN with a dense positronium cloud. In order to produce enough positronium, it is necessary to realize an intense source of slow positrons, a few 10^8 per second. This is done with a small electron linear accelerator. A few 10^{10} positrons are accumulated every cycle in a Penning–Malmberg trap before they are ejected onto a positron-to-positronium converter. The overall scheme of the experiment is described and the status of the installation of the prototype positron source at Saclay is shown. The accumulation scheme of positrons is given,

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and positronium formation results are presented. The estimated performance and efficiency of the various steps of the experiment are given.

Keywords Antihydrogen · Gravitation · Antimatter

1 Introduction

The aim of the GBAR project is to perform the first test of the Weak Equivalence Principle (WEP) with antimatter. The Einstein Equivalence Principle is at the heart of general relativity, it has been tested with a very high precision with matter, but no conclusive direct test with antimatter is available. This is a basic scientific question, the interest of which is enhanced by the unknown origin of the acceleration of the expansion of the universe and by the hypothetical presence of dominant quantities of dark matter: these observations suggest that our understanding of gravitation may be incomplete. Extensions of gravitation theory can lead to differences in behavior between matter and antimatter (see for example [1]). Some authors have even discussed the possibility of antigravity within general relativity [2]. Indirect tests of the Equivalence Principle for antimatter have been obtained by comparing the properties of particles and their antiparticles or by arguing about the virtual content of the nuclei of ordinary matter. Two particle-antiparticle systems have been studied in great detail with this aim: the $K^0 - \bar{K}^0$ system (comparison of decay parameters [3]), and the $p - \bar{p}$ system (simultaneous measurement of both cyclotron frequencies [4]). However, all these tests rely upon disputable theoretical hypotheses—refer for example to the review [5] on experimental and theoretical arguments. One should also note that some authors have published a limit on the mass difference between neutrinos and antineutrinos from the time arrival of events from the 1987A supernova explosion [6], but this limit assumes that at least one out of the 19 observed events is due to an electron neutrino, the other ones being due to antineutrinos. This hypothesis could not be verified.

Previous attempts to test the WEP with positrons [7] and antiprotons [8] have been considered, but it turned out to be too difficult to reduce electromagnetic effects sufficiently. It seems also out of present reach to perform gravity experiments with antineutrons [9] or positronium [10]. The antihydrogen atom is the next simplest candidate system

2 Principle of the GBAR experiment

The principle of the GBAR experiment has been described in a Letter of Intent to CERN [11]. Its originality is to produce and cool down to about 20 μK $\overline{\mathrm{H}}^+$ ions to provide ultra-cold neutral $\overline{\mathrm{H}}$ atoms by photodetachment of the extra positron. Its gravity acceleration, call it $\bar{g}$, can then be determined by measuring the time of its free fall down a few tens of cm. This method has been proposed in [12], but that paper did not address the production of enough $\overline{\mathrm{H}}^+$ ions. The main source of uncertainty comes from the initial speed of the anti-atom, and the precision on $\bar{g}$ is mainly statistical. About 10^4 ions are needed to reach a precision below 1%. $\overline{\mathrm{H}}^+$ ions can be produced in a two-step process: $\overline{p} + Ps \rightarrow \overline{H} + e^-$ followed by $\overline{H} + Ps^* \rightarrow \overline{H}^+ + e^-$. Because the production cross sections are very low (see the measurement of the matter counterpart of reaction 1 in [13], and the estimate for reaction 2 in [14]), the experiment relies on the production of large quantities of low energy (in the keV range) antiprotons, and on a very high flux of positrons, well above the capacity of ^{22}Na sources, in order to produce enough Ps. The overall scheme of the measurement is thus as follows:

1. 5–10 MeV electrons from a small linear accelerator are sent onto a tungsten target and produce fast positrons;
2. the emitted positrons are moderated down to 3 eV and stored in a Penning–Malmberg trap;
3. once enough positrons are accumulated, they are ejected and dumped onto a positron-positronium converter;
4. a laser pulse allows the excitation of a fraction of the Ps to enhance the $\overline{H}^+$ production yield;
5. in coincidence, antiprotons from the antiproton decelerator (AD) at CERN cross the newly formed dense positronium cloud;
6. the few $\overline{H}^+$ ions produced are selected, decelerated and trapped in a segmented Paul trap, where they are sympathetically cooled with beryllium ions;
7. the excess positron is photodetached at threshold and the free fall time of flight is measured by detecting both the $\overline{p}$ and the e^+ annihilations on a plate below the trap.

Steps 1 to 4 are to be tested at CEA Saclay before the experiment, if accepted, is installed at CERN. The following sections address each step in more detail.

3 Slow positron production

In the original scheme [11], a 5.5 MeV accelerator sending 4 μs bunches at a rate of 200 Hz with a mean current of 0.14 mA onto a thin tungsten target produces a flux of about 10^{11} fast e^+s^{-1}. In a first stage of the experiment, positrons will be moderated to 3 eV with a tungsten moderator close to the target, with an efficiency expected to be about 10^{-4}. In a later stage, a solid neon moderator installed after an e^+/e^- magnetic separator could allow a few 10^{-3} efficiency, leading to a flux of 10^7 to 10^8 slow e^+s^{-1}. A prototype accelerator with a somewhat lower energy (4.3 MeV) and the magnetic separator have been installed at Saclay. The extracted positron yield has been measured at the expected rate on a detector made of 35 Faraday cups (Fig. 1). The slow positron extraction beam line is now being mounted (Fig. 2).

Slow positrons will be stored in the RIKEN Multi Ring Trap (MRT) described in [15] with which 10^6 positrons from a ^{22}Na source could be stored with a 1% trapping efficiency. The trap mainly consists of a 5 T superconducting solenoid and 23 ring electrodes. It is now at Saclay, and the accumulation scheme will be adapted to the bunched beam. The aim is to store a few 10^{10} positrons in a few minutes. Slow positrons have to be bunched and re-accelerated to about 1 keV to pass the magnetic mirror and be trapped before they make a round trip (85 ns delay) (see Fig. 3). They are cooled down in less than 5 ms by a previously injected electron plasma of 10^{17} m^{-3}

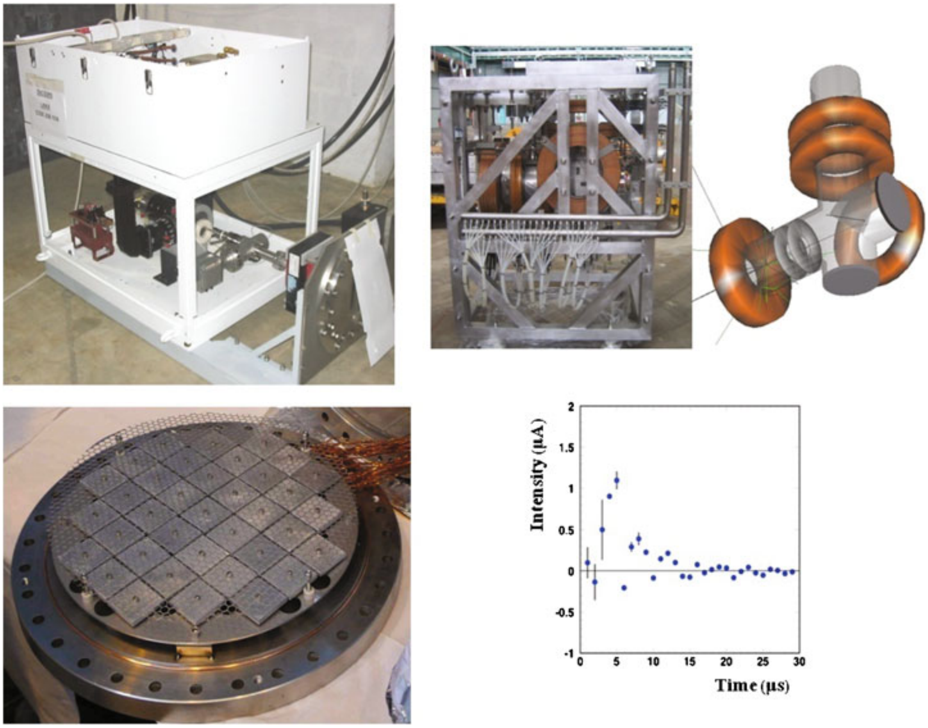
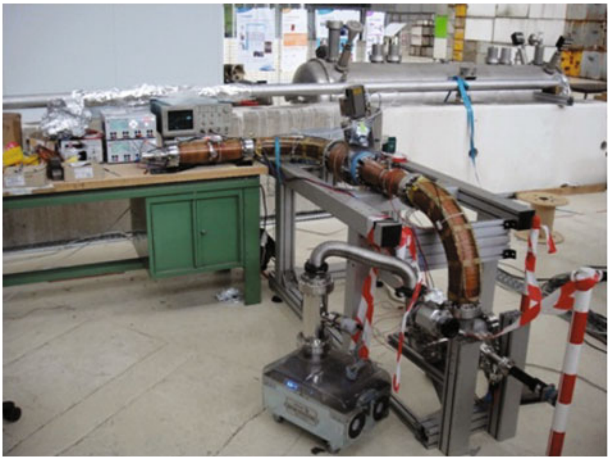


Fig. 1 *Top left*: prototype linac; *top right*: positron magnetic separator; *bottom left*: fast positron detector; *bottom right*: typical positron signal seen on detector pads

Fig. 2 The slow positron beam line under installation and tests at Saclay



density. With this scheme, there is no need for remoderation of the positrons inside the MRT as in [15], and since the positrons are bunched and not continuously emitted from a source, the expected overall trapping efficiency is in excess of 20%.

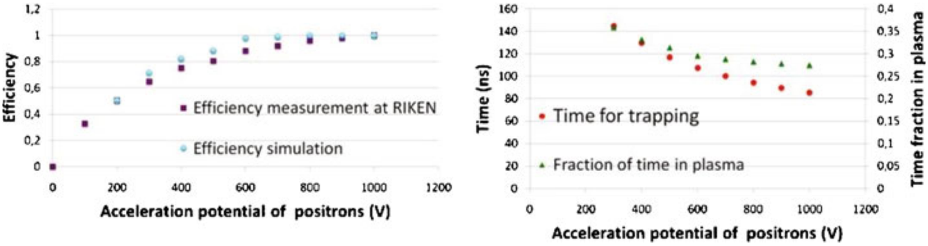
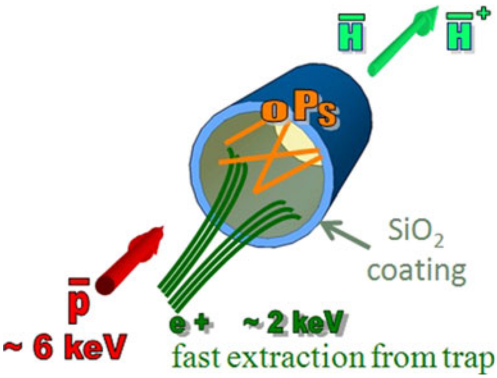


Fig. 3 As a function of the acceleration potential: *left*—efficiency for positrons from a ^{22}Na source to pass the magnetic mirror of the RIKEN MRT; *right*—round trip time of positrons in the MRT and fraction of time spent by positrons in the electron cloud

Fig. 4 Artist's view of the geometry of the positron-positronium converter



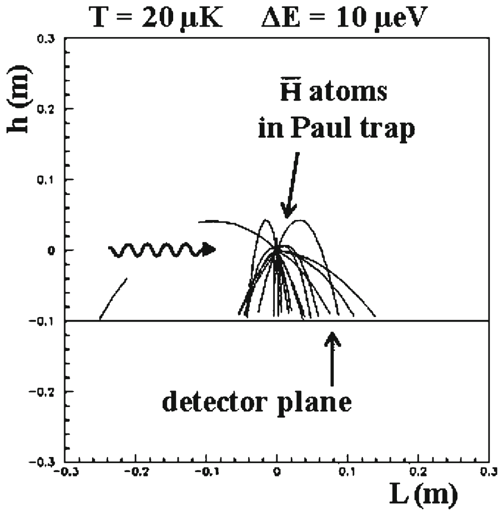
4 Production of a dense positronium target

To produce a dense positronium cloud, positrons accumulated in the trap have to be dumped on a converter material in less than 142 ns, the oPs lifetime in vacuum. Conversion of positrons to positronium has been tested with various samples of nanoporous SiO_2 at CERN with the ETHZ positron beam [16, 17] and at UCR [18]. The emitted positronium kinetic energy can be as low as 40 meV at a few keV implantation energy. In addition, the conversion efficiency remained above 30% with positron fluxes as different as 3.5×10^5 cm^{-2}s^{-1} from a radioactive source at CERN and 5.6×10^{16} cm^{-2}s^{-1} dumped from a trap at UCR. Thanks to the low energy of the positronium, it is intended to keep a high Ps density of order 10^{12} cm^{-2} by using a closed geometry—a tube of 1 mm diameter—for the converter (Fig. 4), since it is expected that SiO_2 reflects a large fraction of Ps. This method will be tested at Saclay.

5 Production of ultra cold $\overline{\mathrm{H}}$ atoms

In coincidence with the formation of the positronium cloud, a bunch of 10^7 antiprotons is sent to cross that cloud. The aim is to produce $\overline{\mathrm{H}}^+$ ions via the two-step process: $\bar{p} + \mathrm{Ps} \rightarrow \overline{\mathrm{H}} + e^-$ followed by $\overline{\mathrm{H}} + \mathrm{Ps}^* \rightarrow \overline{\mathrm{H}}^+ + e^-$, as oulined in Section 2.

Fig. 5 Typical trajectories of $\overline{\text{H}}$ atoms after photodetachment. The *curvy arrow* indicates the laser beam direction. The temperature is assumed to be 20 μK, and the laser is tuned 10 μeV above threshold



The cross section of the matter counterpart of the first reaction has been measured above 10 keV and estimated over a wider energy range (see [13] and references therein). It is of the order of 10^{-15} cm^2, with a strong variation with energy. The second reaction has not been measured. In [14], the estimate for its matter counterpart is about 10^{-16} cm^2. However, because the binding energy of the n = 3 positronium state is 0.75 eV and is very close to that of $\overline{\text{H}}^+$, the cross section is expected to be strongly enhanced with excited positronium. Such kind of effect has been calculated with n = 2 Ps states [19]. The cross section increase is strongly dependent on the incident energy. The optimization of the whole formation process is under way, this involves the theoretical calculation of the n = 3 cross section, the optimization of the fraction of Ps to be excited, and the choice of the antiproton kinetic energy. First estimates show that it is reasonable to expect a factor 10 enhancement on the $\overline{\text{H}}^+$ production above the previous numbers. This would lead to about 10 ions produced with 2.5×10^{10} positrons and 10^7 antiprotons.

With the present performances of the Antiproton Decelerator at CERN, it would take about 20 min to accumulate this number of slow antiprotons, and a dedicated trap would have to be used. If the Extra Low Energy Antiproton ring (ELENA) project is accepted, antiprotons could be decelerated and directly guided onto the Ps target without any intermediate storage. This would simplify the experimental installation.

The $\overline{\text{H}}^+$ ions have almost the same energy as the incident antiprotons. They have to be selected and slowed down to enter a segmented Paul trap where they will undergo sympathetic cooling with Be^+ ions. Because the typical well depth of a Paul trap is about 1 eV, the capture of the ions needs to be designed carefully. It has been shown that Be^+ ions can be cooled to temperatures below 10 μK [20]. The sympathetic cooling to less than 20 μK of $\overline{\text{H}}^+$ ions has to be demonstrated. Detailed simulations are underway.

For practical reasons, the free fall of the $\overline{\text{H}}$ atom will be performed on a few tens of cm height and will last a few tenths of a second (assuming $\bar{g} = g$!). The

Table 1 Estimated performances and efficiencies

Electrons				
Linac energy	Electron rate			
5.5 MeV	$8.8\ 10^{14}\ s^{-1}$			
Positrons				
Production efficiency	Transport efficiency	Moderation efficiency	Fast positron rate	Slow positron rate
$1.5\ 10^{-4}$	80%	10^{-3}	$1.1\ 10^{11}\ s^{-1}$	$1.1\ 10^{8}\ s^{-1}$
Positron storage				
Trapping efficiency	Storage time	Stored positrons		
20%	1200 s	$2.5\ 10^{10}$		
Positronium				
Production efficiency	Tube volume	Positronium density	Gain in cross section from Ps excitation	
35%	$10\ mm^3$	$8.8\ 10^{11}\ cm^{-2}$	10	
Antihydrogen				
Antiprotons per 20 min	Production cross section of the atom	Production cross section of the ion	$\overline{\mathrm{H}}$ per 20 min	$\overline{\mathrm{H}}^+$ per 20 min
10^7	$10^{-15}\ cm^2$	$10^{-16}\ cm^2$	$8.8\ 10^4$	~ 8

precise value of the detection parameters will only be fixed after optimization with a realistic simulation. To perform the measurement of the free fall of the $\overline{\mathrm{H}}$ atom, the photodetachment of the bound positron from the ion has to be done very close to threshold with a tunable laser system to avoid a too large recoil which would prevent making the measurement. One recoil is due to the absorption of the photon, the recoil velocity is 0.2 m/s, and the direction can be chosen to be horizontal. The second recoil is due to the emitted positron. If the photon is tuned to below 10 μeV above threshold, the recoil velocity remains below 1 ms^{-1}. The cross section of the photodetachment will be very low, but the laser power can be focused on a very small volume, because the ions can be localized to about 10 μm. From measurements [21] and using the $\Delta E^{3/2}$ law at threshold [22], one gets $\sigma \approx 3.8 \times 10^{-16}(\Delta E[eV])^{3/2}cm^2$, leading to a cross section of order 10^{-23} cm^2 at 10 μeV above threshold. With a 1 W laser beam focused on a 100 μm^2 area, the photodetachment rate is about 100 s^{-1} per ion, more than enough to perform all measurements between two antiproton ejections from the AD. Both the laser shot time and the detection of the annihilation of the emitted positron will give the start time of the free fall.

The antiproton and the positron annihilations on a detector plane at a distance h from the trap center will be detected, to measure the duration Δt of the free fall, leading to the acceleration of antihydrogen: $\bar{g} = 2h/\Delta t^2$. Simulations for the design of the detection stage have just started. Typical trajectories of $\overline{\mathrm{H}}$ atoms are sketched in Fig. 5.

By putting all these parameters together, one meets the requirements of the method proposed in [12] and a 1% precision on $\bar{g}$ is reachable with 10,000 detected $\overline{\mathrm{H}}$ ions. Table 1 summarizes the estimated performances and efficiencies of the various steps of the proposed experimental scheme. It is to be noted that if the ELENA project is approved at CERN, and with a higher energy electron accelerator (10 MeV), the production rate of $\overline{\mathrm{H}}$ atoms could be significantly improved.

6 Perspectives

The GBAR collaboration has recently been formed. Based on the initial Letter of Intent [11], the technical design of the experiment is in progress, and a proposal is being prepared. In the next two years, the main objectives will be to test the accumulation of several 10^{10} positrons in the RIKEN MRT at Saclay, and to optimize the positronium cloud formation and excitation. If the project is approved, the installation at CERN and tests with antiprotons will follow. On a longer term, a much higher precision on the measurement of $\bar{g}$ could be reached with a different technique mentioned in [23]: the principle is to do the spectroscopy of gravitational levels of $\overline{H}$, in a way inspired from work with ultra-cold neutrons [24]. This idea looks promising because the $\overline{H}$ atoms are prepared at a very low temperature and in a very compact system.

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