

Status report on the GBAR CERN experiment

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Abstract. GBAR is a recently approved experiment at CERN/AD. Its aim is to perform the first test of the Weak Equivalence Principle with Antimatter. The objective is to measure the gravitational acceleration of antihydrogen atoms on Earth with 1% precision in a first phase, and better than a per mil in a second phase. The method is to detect the free fall of ultracold atoms. By sympathetic cooling of antihydrogen positive ions $\bar{\text{H}}^+$ with beryllium ions, and after photodetachment of the excess positron, antiatoms are formed at m/s velocities and their free fall can be directly measured. Antihydrogen ions are produced by the interaction of keV antiprotons with a dense positronium cloud, the latter being formed by dumping positrons onto a porous material. We describe here briefly the experimental techniques and report on the most recent results. In particular, a flux of around $4 \times 10^6 \text{ e}^+ \text{ s}^{-1}$ slow positrons is now produced by the source installed at Saclay, cross sections for the production of the $\bar{\text{H}}^+$ ions have been computed, and a dedicated beam line for the study of positronium formation and for applications in Materials Science has been realized. The tentative schedule of the GBAR developments is given.

1. Introduction

The GBAR experiment has been approved by the CERN Research Board in May 2012 [1]. Its aim 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 there is no conclusive direct measurement with antimatter. 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.

Indirect tests of the Equivalence Principle for antimatter can be obtained by comparing the properties of particle-antiparticle systems. Two particle-antiparticle systems have provided such limits: the $K^0 - \bar{K}^0$ system (comparison of decay parameters [2]), and the $p - \bar{p}$ system (simultaneous measurement of both cyclotron frequencies [3]). One can also use the WEP tests with matter: because of the matter antimatter virtual pair content of the nuclei, if antimatter is coupled differently to gravitation from matter, this induces differences between various nuclei. However, as shown in [4], all these tests rely upon debatable theoretical hypotheses.

A limit on the mass difference between neutrinos and antineutrinos has been derived by the comparison of the time arrival of events from the 1987A supernova explosion [5], but this limit relies on the non proven hypothesis that at least one out of the 19 observed events is due to an electron neutrino, the other ones being antineutrino interactions.

Previous attempts to test the WEP with positrons [6] and antiprotons [7] have been launched,



but neither has been completed. It seems also out of present reach to perform gravity experiments with antineutrons [8] or positronium [9]. The antihydrogen atom is consequently the best candidate system.

2. Principle and goal of the experiment

GBAR is described in detail in [10]. The key innovative feature is to produce and cool to around 10 μ K \bar{H}^+ ions to provide ultra-cold neutral \bar{H} atoms by photodetachment of the extra positron. The duration time of their subsequent free fall down a few tens of cm provides a direct measurement of their gravity acceleration (\bar{g}). This method has been proposed by Walz and Hnsch in [11], but the production of enough \bar{H}^+ ions to perform the experiment was not addressed. The main source of uncertainty comes from the initial speed of the anti-atom, and the precision on \bar{g} is mainly statistical. About 1500 ions are needed to reach a 1 % relative precision. This is the goal of the first phase of the experiment.

\bar{H}^+ ions can be produced by two charge-exchange processes: $\bar{p} + \text{Ps} \rightarrow \bar{H} + e^-$ followed by $\bar{H} + \text{Ps} \rightarrow \bar{H}^+ + e^-$. Because the cross sections of these reactions are very low, 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 as follows:

- Electrons of 10-20 MeV from a small linear accelerator are dumped onto a tungsten target and produce fast (MeV) positrons.
- The emitted positrons are moderated down to 3 eV and accumulated in a Penning-Malmberg trap.
- Once a few 10^{10} positrons are stored, they are ejected onto a positron-positronium converter.
- a laser pulse allows the excitation of a fraction of the Ps to enhance the \bar{H}^+ production yield ;
- In coincidence, 100 keV antiprotons are extracted from the antiproton decelerator AD followed by the ELENA ring presently in construction at CERN ; they are decelerated further down to a few keV and directed towards the newly formed dense positronium cloud.
- The \bar{H}^+ ions produced are selected, decelerated and trapped in a segmented Paul trap, where they are sympathetically cooled with beryllium ions.
- The excess positron of \bar{H}^+ is photodetached at threshold and the free fall duration time is measured by detecting the antihydrogen atom annihilation on a plate below the trap with time projection chambers and scintillating counters. Because of the unknown initial velocity, \bar{g} has to be statistically extracted.

3. Slow positron production

A prototype slow positron source is installed at IRFU at Saclay. It comprises a 4.3 MeV electron linear accelerator producing bursts of 2.5 μ s effective length at 200 Hz with 140 μ A mean current, a 1 mm tungsten target, and a moderator made of a stack of tungsten meshes. Figure 1 shows the e^+ yield for various moderator setups. The optimization is still under way. The present achieved positron rate is in the range $3\text{-}4 \times 10^6 \text{ s}^{-1}$. It is comparable to rates obtained with the most intense ^{22}Na radioactive sources. The target rate for GBAR is $3 \times 10^8 \text{ s}^{-1}$. It will be reached by increasing the electron accelerator energy and repetition rate, and by improving the moderation technique.

4. Positron accumulation

Slow positrons are guided through a vacuum pipe by a 8 mT magnetic field to a Multi Ring Trap provided by the RIKEN atomic laboratory, and described in [12]. With a 3 T magnetic field in

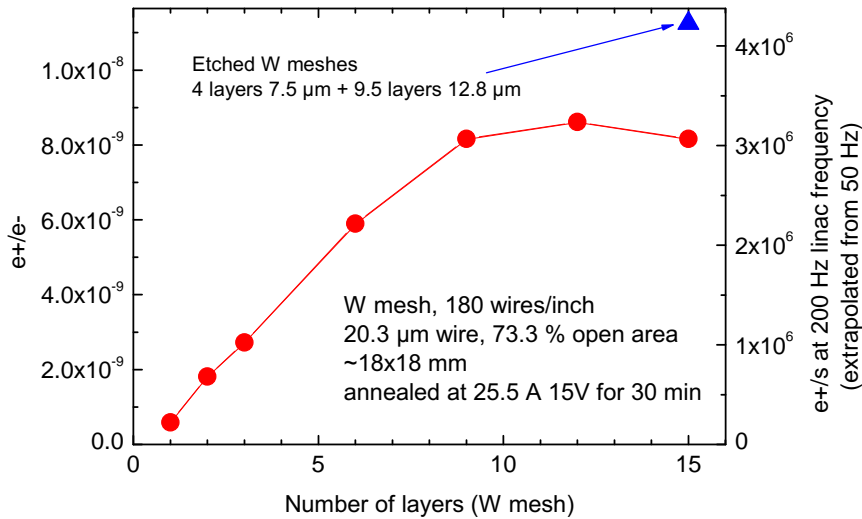


Figure 1. Positron yield as a function of the number of W meshes layers. Annealing of W meshes at high temperature is necessary to obtain a good moderation efficiency. Chemical etching can also improve the yield as shown by the blue triangle. The diameter of the mesh wires is another relevant parameter.

the trap, the transport efficiency into the trap has been measured to be close to 100% when an acceleration voltage of 1.6 kV is applied at the entrance of the trap to pass the magnetic mirror. The trapping scheme will take advantage of the pulsed slow positron beam: positrons are injected in the trap by lowering the voltage of the entrance electrode; the potential is restored before positrons make a round trip. They are slowed down by Coulomb interactions with a preloaded electron plasma, and are eventually trapped in a potential well in less than 3 ms, before the next burst arrives and the entrance electrode is lowered again. Because it takes 80 ns for positrons to make a round trip in the trap, it is necessary to bunch the positron beam. The present method is to apply an increasing voltage during the burst so that late positrons are faster than early ones. Because of the energy and angular dispersion of the positrons emitted by the moderator, the bunching efficiency is only around 30%. A dedicated buncher will be necessary to improve this efficiency. The setup is now ready to perform systematic studies of the trapping mechanism.

5. Production of a dense positronium target.

Orthopositronium (oPs), which has a lifetime of 142 ns in its ground state, is produced by dumping the positrons accumulated in the trap in less than 100 ns on a converter material, the one presently used is the nanoporous SiO₂. The production efficiency has been measured to be as high as 30% [13, 14, 15]. To further study and optimize the positronium production, a secondary beamline has been assembled end of 2012 (Figure 2). This line will also be used for applications in Materials Science.

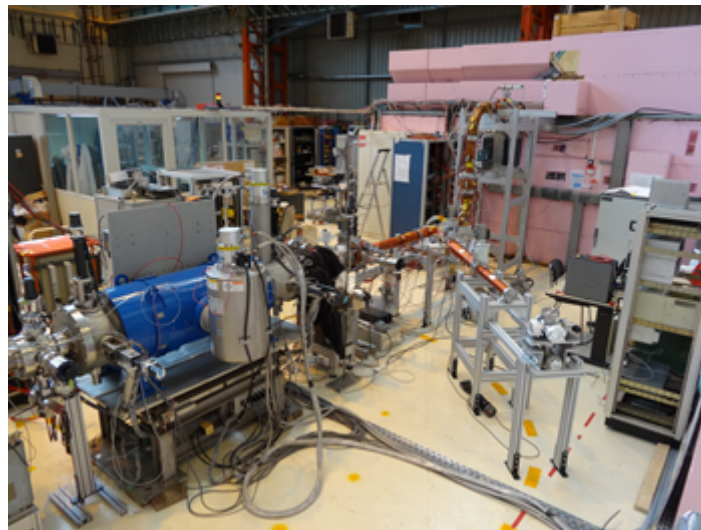


Figure 2. Photograph of the experimental setup at Saclay. One sees on the left the main positron beam line with the Riken trap, and on the right the secondary beam line.

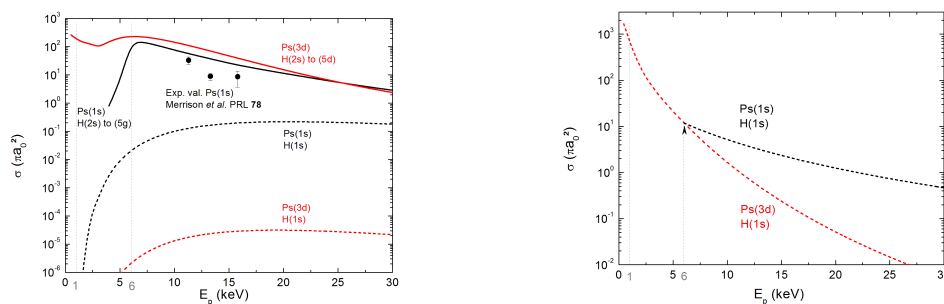


Figure 3. Cross-section in atomic units for the reactions $\bar{p} + \text{Ps}^{(*)} \rightarrow \bar{\text{H}}^{(*)} + e^{-}$ (left) and $\bar{\text{H}} + \text{Ps}^{(*)} \rightarrow \bar{\text{H}}^{+} + e^{-}$ (right) as a function of the antiproton kinetic energy

6. Production of antihydrogen positive ions

In coincidence with the formation of the positronium cloud, a bunch of 5×10^7 antiprotons is directed to cross that cloud. $\bar{\text{H}}^{+}$ ions are produced via the two-step process: $\bar{p} + \text{Ps} \rightarrow \bar{\text{H}} + e^{-}$ followed by $\bar{\text{H}} + \text{Ps} \rightarrow \bar{\text{H}}^{+} + e^{-}$. The cross section of the matter counterpart of the first reaction has been measured above 10 keV and estimated over a wider energy range [16]. It is of the order of 10^{-15} cm^2 , with a strong variation with energy. The second reaction has not been experimentally verified. In [17], 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 $\bar{\text{H}}^{+}$, the cross section is expected to be strongly enhanced with excited positronium. The cross section of these processes have been recently evaluated for different excited states of the antihydrogen atoms and of the positronium [18]. The cross section increase is strongly dependent on the incident energy (Figure 3). The optimization of the whole formation process is under way, it involves the optimization of the fraction of Ps to be excited, the choice of the antiproton kinetic energy, the duration of the laser pulse, and the length of the reaction chamber.

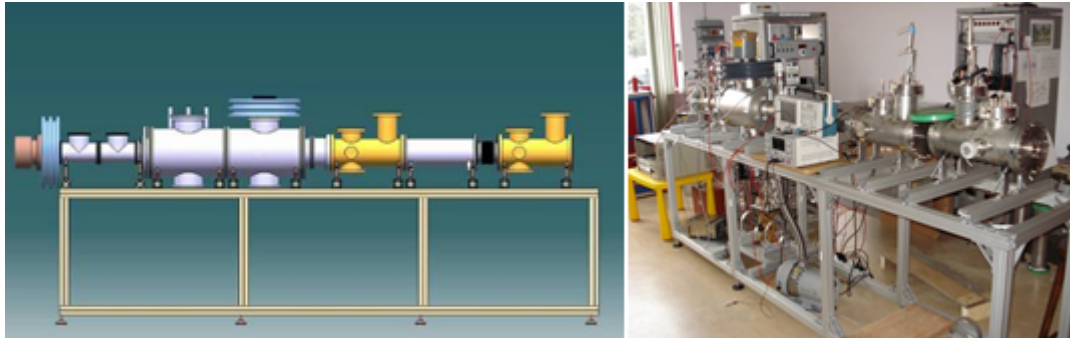


Figure 4. Schematic (left) and photograph (right) of the decelerator test bench in Orsay.

First estimates show that it is reasonable to expect one \bar{H}^+ per delivered antiproton bunch. The Ps production and excitation will be tested at CEA Saclay in 2014.

To maximize the \bar{H}^+ yield, antiproton kinetic energy must be in the range 1 to 6 keV. This is much lower than the expected 100 keV energy which will be provided by the ELENA ring. It will thus be necessary to further decelerate the antiprotons. This will be done with an electrostatic decelerator tube. This method has been experienced at ISOLDE on 60 keV ions. Very good efficiencies can be obtained (see for example [19]). With the updated parameters of ELENA, a preliminary estimate of the efficiency to transport the decelerated antiproton beam to the reaction chamber is around 40%. The decelerator is being realized at Orsay CSNSM for tests with protons (Figure 4).

7. Cooling of the antihydrogen ions

The \bar{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. The method is described in detail in the proposal. It has been shown that Be^+ ions can be cooled to temperatures below 10 μK [21]. However, the sympathetic cooling of \bar{H}^+ ions to less than 10 μK is a double challenge : sympathetic cooling followed by side-band cooling in a Paul trap with such a large charge/mass difference between the ion species has not been demonstrated, and it will be the first time that one attempts this technique with antimatter, for which losses of antiatoms must be avoided. Detailed simulations are under way, and the technique will be developed by LKB and Mainz University with hydrogen ions before installation at CERN.

8. Free fall detection

To minimize the size of the ultra-vacuum chamber, the free fall of the \bar{H} atom will be performed on a few tens of cm height. It will last a few tenths of a second (assuming $\bar{g} = g$!). The photodetachment of the bound positron from the ion has to be done very close to threshold to avoid a too large recoil which would prevent making the measurement with a detector of reasonable size. The first recoil is due to the absorption of the photon, it is harmless since the recoil velocity is 0.2 ms^{-1} , 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 around 10 μm . From measurements [22, 23], one gets $\sigma \approx 4 \times 10^{-16} (\Delta E [eV])^{3/2} \text{ cm}^2$, 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 $100\ \mu\text{m}^2$ area, the photodetachment rate is around $100\ \text{s}^{-1}$ per ion, more than enough to perform all measurements during the delay between two antiproton ejections from the AD (110 s). The laser shot time will give the start time of the free fall.

The antihydrogen annihilation on a detector plane at a distance h from the Paul trap center will be detected and the duration Δt of the free fall measured, leading to an estimate of the acceleration of antihydrogen: $\bar{g} = 2h/\Delta t^2$, assuming a null mean initial velocity of the antiatoms. The detector will consist in a set of Time Projection Chambers covering as much as possible of the vacuum chamber to reconstruct the vertex position of the antihydrogen annihilation and reject the cosmic background, and scintillator counters surrounding the whole setup to measure the annihilation time.

By putting all parameters together, one meets the requirements of the method proposed in [11] and a 1 % precision on \bar{g} is reachable in a few weeks of running time, enough to accumulate a few thousands detected $\bar{\text{H}}$ ions.

9. Perspectives

It will be possible to reach a much higher precision by using the Casimir effect in the same way as was demonstrated with ultra-cold neutrons [24] : if the detector plane is a few micron below the Paul trap centre from where the ultra-cold $\bar{\text{H}}$ atoms are released, those are reflected with very high probability by the detector plane. They are trapped by the gravitational field. Their height is quantized and the energy levels are proportional to the gravitational mass, allowing a measurement of \bar{g} to 10^{-3} relative precision with a few hundreds events.

10. Collaboration and tentative schedule

The GBAR collaboration gathers 48 physicists from 14 institutes covering the many fields needed to perform the experiment : accelerator, particle and atomic physics, plasma trapping, positronium and materials science, antihydrogen formation, laser cooling and atom manipulation, gravitational spectrometry : CSNSM Orsay, ETH Zurich, ILL Grenoble, IPCMS Strasbourg, IRFU Saclay, Lebedev Moscow, LKB Paris, JGU Mainz, NCBJ Otwock Swierk, RIKEN, Swansea University, University of Tokyo Komaba, Tokyo University of Science, Uppsala University.

GBAR was approved by CERN Research Board in May 2012. Tests of trapping positrons have started at Irfu Saclay. The deceleration technique will be tested in 2013 at CSNSM Orsay. The positronium formation and excitation will be measured in 2014. The free fall detector is expected to be ready for tests by 2015. The sympathetic cooling must be first demonstrated with ordinary matter ions by LKB and Mainz University before the installation at CERN. A new electron accelerator will be built at NCBJ in Poland by 2015. Commissioning of the experiment should start in 2016. The physics run is scheduled for 2017.

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