GBAR
Gravitational Behavior of Antihydrogen at Rest

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The GBAR experiment aims to test the Equivalence Principle with antimatter by measuring the time of flight of ultra-cold antihydrogen atoms $\bar{H}$ in free fall. Antihydrogen atoms at ~20 μK are provided by sympathetic cooling of antihydrogen ions $\bar{H}^+$ with laser cooled Be^+ ions. $\bar{H}^+$ ions are produced via two successive reactions using antiprotons and positroniums. The synthesis of $\bar{H}^+$ is obtained by the injection of a pulse of 10^7 slow antiprotons from the AD at CERN in a dense cloud of positronium. This target of positronium is created with a positron-to-positronium converter and requires an intense source of slow positrons, a few 10^8 per second. Such a source based on a small electron accelerator is under construction at Saclay. A few 10^{10} positrons are accumulated in a Penning-Malmberg trap from which they are ejected towards the e^+/Ps converter to produce the target. The overall scheme of the experiment is described along with the estimated efficiency of each step.

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 [1].

Direct tests have been attempted with positrons [2] and antiprotons [3], but they turned out to be too difficult to reduce electromagnetic effects sufficiently. It seems also out of present reach to perform gravity experiments with antineutrons [4] or positronium [5]. The antihydrogen atom is the next simplest candidate system. Indirect tests of the Equivalence Principle for antimatter have been obtained by comparing the properties of particles and their antiparticles (such as p-$\bar{p}$ [6] and K_0-$\bar{K}_0$ [7]) or by arguing about the virtual content of the nuclei of ordinary matter. However, all these tests rely upon disputable theoretical hypotheses - refer for example to the review [8] on experimental and theoretical arguments.

2 Principle of the GBAR experiment

The GBAR experiment will measure the time of flight of ultra-cold antihydrogen atoms in free fall. The principle of GBAR has been described in a Letter of Intent to CERN [9]. The original way to produce ultra-cold $\bar{\mathrm{H}}$ atoms at ~20 μK consists to cool down $\bar{\mathrm{H}}^+$ ions via sympathetic cooling with laser cooled beryllium ions Be^+. Then $\bar{\mathrm{H}}^+$ ions are neutralized by photodetachment of their extra positron and the $\bar{\mathrm{H}}$ atoms produced fall freely in the gravitational potential of the Earth. The height h of the free fall is of the order of ten centimeters. The gravity acceleration, called $\bar{g}$, is determined by measuring the time Δt between the photodetachment and the annihilation of $\bar{\mathrm{H}}$ in the walls of the experiment, $\bar{g} = 2h/(\Delta t)^2$ (figure 1).

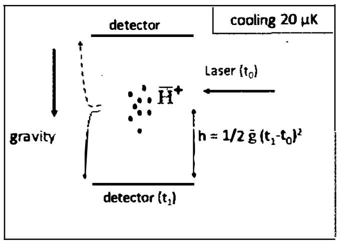

Figure 1: Scheme of the $\bar{g}$ measurement.

The main source of uncertainty comes from the initial velocity of the anti-atom. The precision on $\bar{g}$ is mainly statistical. About 10^4 measures are needed to reach a precision below 1%. This method has been proposed by J. Walz and T. W. Hänsch[10], but they did not describe the way to produce the $\bar{\mathrm{H}}^+$ ions. These ions are produced via two successive reactions (1) and (2) using antiprotons $\bar{\mathrm{p}}$ and positroniums Ps:

$$\bar{\mathrm{p}} + \mathrm{Ps} \rightarrow \bar{\mathrm{H}} + \mathrm{e}^- \qquad (1)$$

$$\bar{\mathrm{H}} + \mathrm{Ps} \rightarrow \bar{\mathrm{H}}^+ + \mathrm{e}^- \qquad (2)$$

The cross section of the first reaction has been measured for its matter counterpart[11]. The one of the second reaction has been estimated[12]. These cross sections are very low and require the production of large quantities of low energy (in the keV range) antiprotons, and a very high flux of positrons, well above the capacity of β^+ 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 dumped onto a tungsten target and produce fast positrons
2. These positrons are moderated to the electrovolt and accumulated in a Penning-Malmberg trap.
3. Once the required amount of positrons is stored, they are ejected and dumped onto the positron-to-positronium converter.
4. The antiprotons pulse is synchronously injected in the newly formed positronium cloud.
5. The few $\bar{\mathrm{H}}^+$ ions produced are decelerated and trapped in a segmented Paul trap, where they are sympathetically cooled with beryllium ions.
6. The extra positron is photodetached and the free fall time of the produced $\bar{\mathrm{H}}$ is measured.

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

3 Slow positrons production

Our intense source of slow positrons is based on a small linear accelerator. It delivers 4 μs bunches of 5.5 MeV electrons at a rate of 200 Hz with a mean current of 0.14 mA. Electrons are dumped onto a tungsten target in order to produce electron/positron pairs via the Bremsstrahlung radiation of the injected electrons. The efficiency of production of positrons downstream the target has been simulated with GEANT4. It is expected to be about 10^{-4} corresponding to a flux of about 10^{11} fast e^+s^{-1}. In a first stage, fast positrons are moderated from MeV to eV energies with a tungsten foil close to the target, with an efficiency expected to be about 10^{-4}. In a second stage, a solid Neon moderator will be set after an e^+/e^- selector, with a moderation efficiency of a few 10^{-3}. This cryogenic system[a] cannot be placed directly after the tungsten target because of the energy deposit of the escaped electrons. The expected flux of slow positrons is 10^7 to 10^8 e^+s^{-1} depending on the moderator.

Slow positrons will be stored in the RIKEN Multi Ring Trap (MRT). The positron accumulation technique with this kind of electromagnetic trap has been developed by N. Oshima *et al* with a continuous positron beam from a ^{22}Na source [13]. They succeeded to store 10^6 positrons with 1% trapping efficiency. This trap consists of a 5T superconducting solenoid and a set of 23 ring electrodes. The uniform magnetic field confines radially the antiparticles. An electrostatic potential well confines them along the direction of the field. Positrons are cooled down in the trap by Coulomb-collisional damping in an electron plasma. This accumulation technique will be adapted to the pulsed beam in order to store a few 10^{10} e^+ in a few minutes. Slow positrons have to be bunched and reaccelerated to about 1 keV to go through the magnetic mirror and be trapped before they make a round trip in 85 ns (see figure 2). They are cooled down in less than 5 ms in a previously injected electron plasma of 10^{17} m^{-3} density, the expected overall trapping efficiency is in excess of 20 %.

Figure 2: As a function of the acceleration potential. Left: efficiency for slow positrons to go through 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 plasma.

The linear accelerator, the e^+/e^- selector and the RIKEN MRT have been installed at Saclay and the slow positrons beam line is under construction (figure 3).

4 Production of the dense positronium target

The positronium target is produced with a e^+/Ps converter. It is a nanoporous SiO_2 material. Positrons are injected onto the converter and catch an electron into the pores. A part of the Ps thus formed diffuses in the porous network until the surface and is ejected in the vacuum.

[a]the melting point of Neon is about 13 K

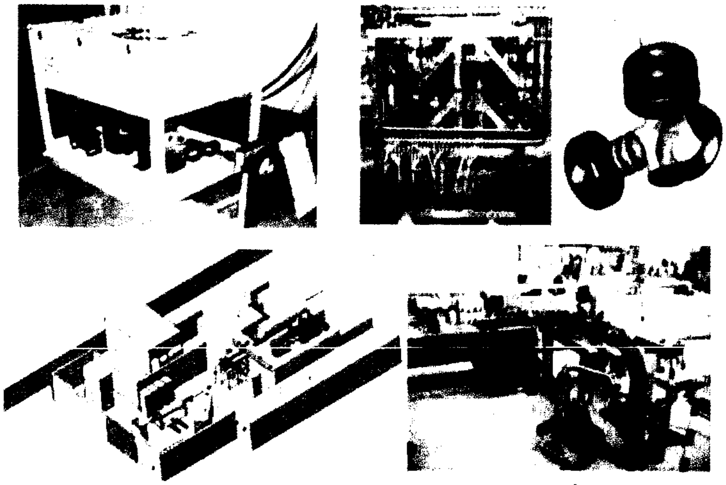

Figure 3: Top left : prototype linac. Top right : positron magnetic separator. Bottom left: design of the experiment at Saclay. The linac and the magnetic separator are in a bunker. They are connected to the cylindrical trap with the slow positron beam line.. Bottom right : slow positron beam line under installation and tests.

This converter has been tested at CERN with the ETHZ positron beam [14,15] and at UCR [16]. The conversion efficiency is above 30% with positron fluxes as different as 3.5×10^{5} $e^{+}cm^{-2}s^{-1}$ from a radioactive source at CERN and 5.6×10^{16} $e^{+}cm^{-2}s^{-1}$ dumped from a trap at UCR. The emitted positronium kinetic energy can be as low as 40 meV at a few keV implantation energy. The cylindrical geometry of the converter with an inner diameter of 1mm and the low energy of positroniums keep a high Ps density of order 10^{12} cm^{-2} (figure 4,a).

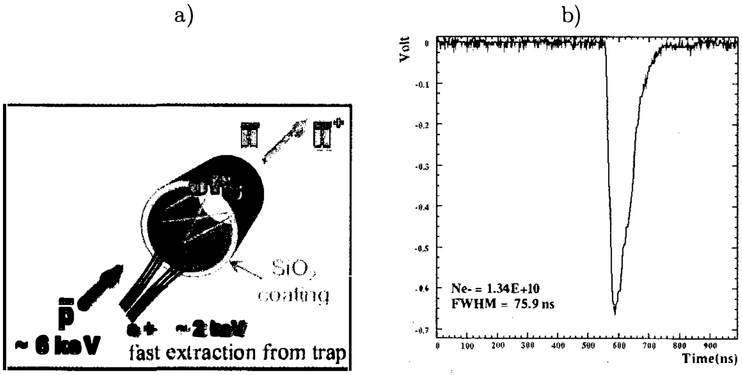

Figure 4: a) Artists view of the geometry of the positron-positronium converter. b) Pulse of 1.3×10^{10} e^{-} ejected from the RIKEN trap in 76 ns.

To produce this dense cloud of Ps, positrons stored in the trap are dumped in the converter in less than 142 ns, the oPs lifetime in vacuum. This fast ejection has been tested with 10^{10} electrons in less than 80 ns with the RIKEN trap (figure 4,b).

5 Production of ultra-cold $\bar{H}$

A bunch of 10^7 antiprotons is injected into the Ps cloud newly formed in order to synthesize $\bar{H}^+$ ions via the two successives reactions 1 et 2. This amount of $\bar{p}$ can be delivered in about 20 minutes by the Antiproton Decelerator at CERN (in 85 s by ELENA upgrade) and will be previously accumulated in a dedicated trap.

The cross section of thc matter counterpart of the first reaction has been measured [11] above 10 keV for the $\bar{p}$ energy and estimated over a lower energy range at an order of 10^{-15} cm^2. The second reaction has been estimated [12] for its matter counterpart. Its cross section is about 10^{-16} cm^2. This cross section is expected to be strongly enhanced with n = 3 excited Ps because the binding energy of this positronium state, 0.75 eV, is very close to that of $\bar{H}^+$. Such kind of effect has been calculated with n = 2 Ps states [17]. The cross section increase is strongly dependent on the incident energy. The optimization of the whole process formation is under way, this involves the theoretical calculation of the 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 $\bar{H}^+$ production above the previous numbers. This would lead to about 10 $\bar{H}^+$ ions produced with 2.5×10^{10} positrons and 10^7 antiprotons.

The produced $\bar{H}^+$ ions have almost the same energy as the incident antiprotons. First, they have to be slowed down to enter in a segmented Paul trap where they will be cooled down by sympathetic cooling with Be^+ ions. These ions can be cooled to temperatures below 10 μK [18]. The sympathetic cooling to less than 20 μK of $\bar{H}^+$ ions has to be demonstrated.

Once the $\bar{H}^+$ ions are cooled at $\sim$20 μK, the extra positron is photodetached with a laser. This photodetachment has to be close to the threshold to avoid a too large recoil which would prevent making the measurement.

6 Perspectives

The GBAR collaboration has recently been formed. Based on the initial Letter of Intent [9], the technical design of the experiment is in progress, and a proposal is being prepared. In the next two years, the main objectivcs 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 bc reached with the spectroscopy of gravitational levels of $\bar{H}$ [19]. This idea looks promising because the $\bar{H}$ atoms are prepared at a very low temperature and in a very compact system.

Acknowledgments

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