

Linac-based positron source and generation of a high density positronium cloud for the GBAR experiment

L. Liskay¹, P. Comini¹, C. Corbel², P. Debu¹, P. Dupré³, P. Grandemange³, P. Pérez¹, J-M. Rey¹, N. Ruiz¹, Y. Sacquin¹

¹CEA, Irfu, Centre de Saclay, F-91191 Gif-sur-Yvette, France

²Laboratoire des Solides Irradiés, Ecole Polytechnique, 91128 Palaiseau, France

³CSNSM-IN2P3/CNRS, Université de Paris Sud, 91406 Orsay, France

E-mail: laszlo.liskay@cea.fr

Abstract. The aim of the recently approved GBAR (Gravitational Behaviour of Antihydrogen at Rest) experiment is to measure the acceleration of neutral antihydrogen atoms in the gravitational field of the Earth. The experimental scheme requires a high density positronium cloud as a target for antiprotons, provided by the Antiproton Decelerator (AD) - Extra Low Energy Antiproton Ring (ELENA) facility at CERN. We introduce briefly the experimental scheme and present the ongoing efforts at IRFU CEA Saclay to develop the positron source and the positron-positronium converter, which are key parts of the experiment. We have constructed a slow positron source in Saclay, based on a low energy (4.3 MeV) linear electron accelerator (linac). By using an electron target made of tungsten and a stack of thin W meshes as positron moderator, we reached a slow positron intensity that is comparable with that of ²²Na-based sources using a solid neon moderator. The source feeds positrons into a high field (5 T) Penning-Malmberg trap. Intense positron pulses from the trap will be converted to slow ortho-positronium (o-Ps) by a converter structure. Mesoporous silica films appear to date to be the best candidates as converter material. We discuss our studies to find the optimal pore configuration for the positron-positronium converter.

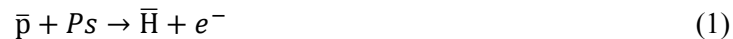
The aim of the GBAR experiment [1] is the direct measurement of the gravitational acceleration of the simplest antiatom, antihydrogen, in the gravitational field of the Earth. Free fall of extremely cold $\bar{\text{H}}$ atoms will be observed and \bar{g} will be determined with better than 1 % precision. The weak equivalence principle for antimatter has never been tested directly. Precision measurement of the gravitational acceleration on charged antiparticles (e.g. positron, antiproton) is rendered impossible by the fact that the residual electromagnetic forces are far stronger than the gravitational one in any conceivable measuring apparatus. On the other hand, deceleration and cooling of neutral particles to the energy range where the measurement of \bar{g} can be performed in the laboratory length scale is very difficult. GBAR is based on an experimental scheme [2] originally suggested by Walz and Hänsch [3]. Positively charged antihydrogen ions ($\bar{\text{H}}^+$, which consist of an antiproton and two positrons) are cooled to nanoelectronvolt energy (10 μK temperature range). The cold ions are then neutralized by photodetachment and the time between the photodetachment and the annihilation of the antiatoms at the bottom (or top) of the experimental chamber is used to determine \bar{g} . The experiment poses a



number of challenges: creation of the $\bar{\text{H}}^+$ ion, its capture and cooling to extreme low energy are steps that have never been achieved before. The present paper, after a brief presentation of the GBAR experimental scheme, gives a short summary of the efforts made at CEA/IRFU to develop the equipment needed to generate the dense positronium cloud, which is a prerequisite for the creation of the $\bar{\text{H}}^+$ ions.

1. The GBAR experimental scheme

A simplified scheme of the GBAR experiment is shown in Figure 1. The antiprotons are provided by the Antiproton Decelerator (AD) facility at CERN. The particles will be further decelerated from 5.3 MeV to 100 keV kinetic energy in the ELENA antiproton storage ring. Finally, the \bar{p} pulses reach a few keV kinetic energy in the switched electrostatic decelerator of the experiment. The antiprotons hit a target consisting of a dense positronium (Ps) cloud. Its density should be sufficiently high so that both charge exchange reactions



that are necessary for the production of the positive ion, take place with sufficient efficiency. The positronium states for the highest possible formation efficiency of $\bar{\text{H}}^+$ in the target cloud will be set by laser excitation. The cross sections of the two reactions are being studied by numerical simulations [4].

The created $\bar{\text{H}}^+$ ions are captured and decelerated to a kinetic energy in the electronvolt range. Cooling to extreme low energy will be achieved in two steps. In the first one the ions will reach a temperature in the mK range by sympathetic cooling with a laser Doppler cooled $^9\text{Be}^+$ cloud. In the final cooling step a $\bar{\text{H}}^+$ - $^9\text{Be}^+$ atom pair will be cooled to the 10 μK temperature range by Raman sideband cooling.

For the photodetachment of the $\bar{\text{H}}^+$ ions a well tuned, horizontally polarized laser beam will be used, in order to minimize the initial velocity of the antihydrogen atoms. The time and place of the annihilation of the antihydrogen atom will be detected by position sensitive detectors, surrounding the experimental chamber. The chamber will provide typically 30 cm distance for the free fall.

2. The positron source

Production of the positronium cloud at every antiproton pulse (typically every 110 s) requires a primary slow positron (e^+) source with more than 10^8 e^+ /s intensity. This intensity is beyond the capability of the currently available isotope-based, solid neon moderated slow positron sources. The planned positron source of the GBAR experiment is based on a linear electron accelerator (linac) with low (up to 20 MeV) beam energy. Positrons will be created by pair production in a cooled tungsten target. In the baseline design, a stack of thin tungsten meshes is used as positron moderator. The moderated positrons will be transported in a weak (typically 8 mT) magnetic field to the positron accumulator, a multi-electrode Penning-Malmberg trap with 5 T magnetic field. At the low transport energy used, most positrons could not pass the magnetic mirror at the entrance of the trap. A special injection system, which forms short (typically 100 ns) bunches from the approximately 3 μs long primary slow positron pulses and accelerates e^+ to kiloelectronvolt kinetic energy before injection into the trap, is being developed to overcome the magnetic mirror effect. The cooling scheme [5,6] uses a cold electron plasma, which is trapped in a separate potential well in the trap. Positrons will be cooled by the trapped electron plasma, and collected in a second potential well. Eventually, approximately 2×10^{10} positrons will be accumulated in the trap. The particles will be ejected in a short (<100 ns) pulse and will hit a positron-positronium converter target.

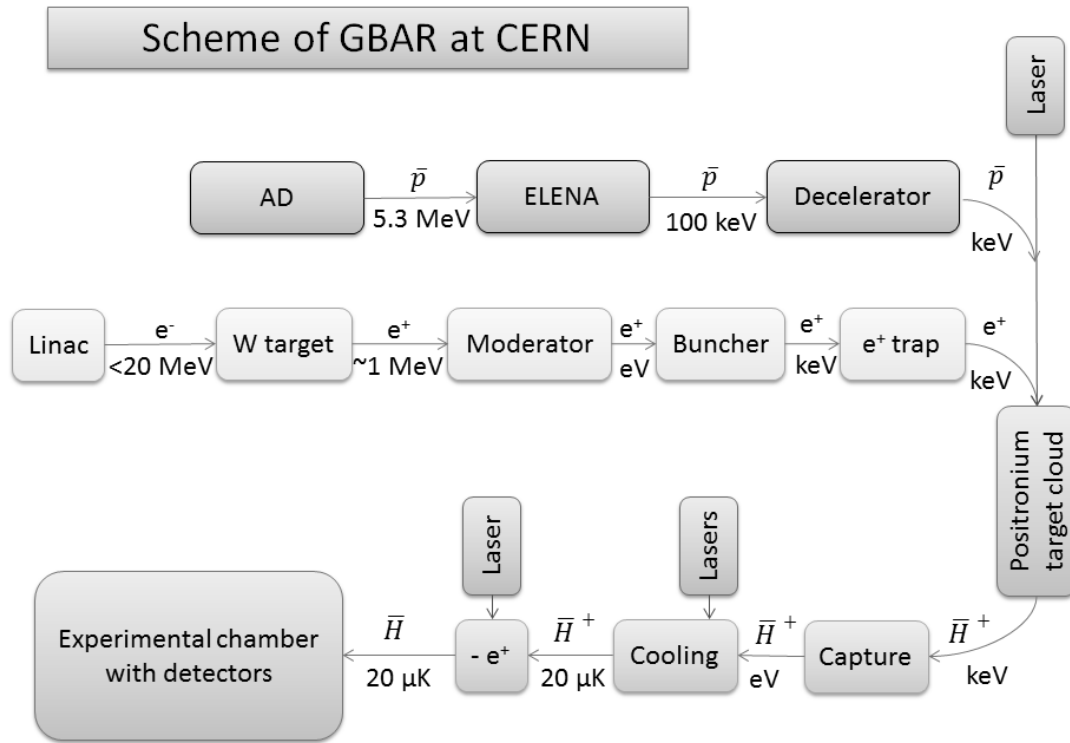


Figure 1 The scheme of the GBAR experiment (AD=Antiproton Decelerator, ELENA=(Extra Low Energy Antiproton Ring).

3. The positronium target cloud

A positronium target cloud with up to 10^{12} Ps/cm³ density is needed for the efficient formation of \bar{H}^+ . Positronium will be formed from the intense positron pulse in a positron/positronium converter structure. The converter should re-emit positronium upon irradiation with e^+ . Only ortho-positronium can be used, as the 125 ps lifetime of the singlet para-positronium state is too short for the reaction with the antiproton pulse. In order to increase the effective density of the positronium cloud, the converter has to emit Ps at low energy. Furthermore, it has to withstand the irradiation with intense e^+ pulses without loss of efficiency. On the basis of the literature and our previous studies [7], the most promising candidate for a e^+ /Ps converter is thin (typically 300-1000 nm) mesoporous silica film, grown on silicon. Ps is created in the film and escapes from the pore system with high (>40 %) efficiency and relatively low energy (<50 meV).

The positronium cloud will be created in a small chamber (Figure 2), typically 1x1x10 mm size. The e^+ /Ps converter forms one side of the chamber. The other three sides are made of a material that reflects Ps with high efficiency. The slow positron pulse will enter the cavity on an open side. It will be then deviated by an electrostatic or magnetic field and the positrons will be implanted into the converter film at approximately 3 keV energy. Ortho-positronium, created in the film and escaping into the cavity, will be confined in the cavity by the reflecting walls. The chamber should give access to the antiproton beam and the laser beam used to excite Ps, and leave place for the exit of the created \bar{H}^+ (and also the much more numerous neutral antihydrogen atoms).

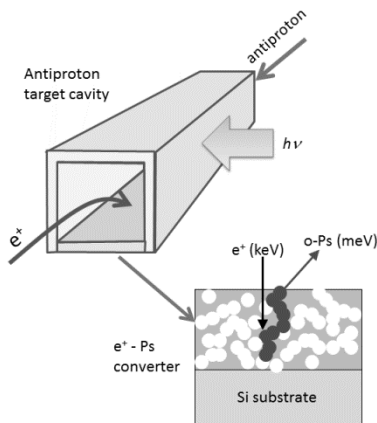


Figure 2 Scheme of the positronium cloud production chamber and the positron-positronium converter film.

4. Development of the e^+ /Ps converter

As the positronium cloud is a key ingredient of the GBAR setup, positronium creation, escape probability and energy should be studied in detail to ensure that a Ps cloud is formed with the density needed for the ion production. Various positron annihilation spectroscopic methods can be used to study positronium creation and escape in thin porous silica films. The most frequently available slow positron beam based detection method uses the measurement of the energy distribution of the annihilation gamma photons. The fraction of positrons which annihilate with three gamma photons can be deduced from these measurements. As most ortho-positronium in vacuum annihilate with three gamma photons, this quantity gives

information on the ortho-positronium escape fraction. However, this detection method is not able to separate o-Ps annihilation in the film (i.e., in pores) from the annihilation events in vacuum. Only positron lifetime spectroscopy can provide full information on the o-Ps escape process. In the design of the lifetime spectrometer and in the analysis of the spectra, care should be taken that the different detection efficiency of different annihilation sites (annihilation in vacuum and annihilation in the film) and the difference between the detection efficiency of 2 gamma and 3 gamma annihilation events do not distort the results. Measurements on mesoporous silica [7,8] have shown that a combination of lifetime and 3 gamma fraction method is an efficient and reliable way to study o-Ps escape in these systems.

The minimum energy of the re-emitted o-Ps is determined by the quantum confinement in the pores [9,10,11]. One way to decrease the energy is by increasing the pore size of the silica, as the zero-point energy decreases with increasing pore size. Measurements on macroporous silica films have shown that films with as large as 32-77 nm pore size exhibit significant (up to 25 %) o-Ps escape fraction [12]. Further studies are underway to find the pore size and porous fraction that gives the optimal o-Ps escape fraction/o-Ps energy combination for the use of the o-Ps converter.

5. The slow positron test source at CEA/IRFU

We developed a slow positron source [13] as a test system for the essential parts of the GBAR setup and to provide slow positrons for positron spectroscopy. It is based on a compact, low energy (4.3 MeV) linac with 200 Hz repetition frequency, 4 μ s pulse length and 100 μ A mean current. The slow positron intensity is approximately 3×10^6 e^+ /s. The slow positron transfer line can supply e^+ for the 5 T Penning-Malmberg trap or to a beam line where slow positron spectroscopy will be performed. A magnetic beam switch is used to move the beam between the two beam lines. To provide a quasi-continuous positron intensity for spectroscopy use, a pulse stretcher has been installed and tested.

6. Summary and outlook

Extrapolation of the measured slow positron yield for higher electron energies shows that the desired positron intensity can be reached at 18-20 MeV linac energy. Further improvement of the positron moderator structure is possible by improving the target-moderator geometry. Attempts will be made to develop a solid neon moderator, which would presumably increase the positron yield significantly. The main elements of the positron cloud production target have been developed; the target cavity has

to be tested first with a low intensity positron beam, then with intensities near the final one. A major challenge is to accumulate 2×10^{10} positrons in the high field trap and eject it into the target cavity within 100 ns. The positron source, together with the antihydrogen ion cooling system and the experimental chamber, has to be installed at the experimental site at CERN by 2016, the expected date of the commissioning of the ELENA ring.

7. Acknowledgement

This work is supported in part by Conseil Général de l'Essonne under ASTRE 2006 funding and by Research National Agency under contract number ANR-05-BLAN-0380-01.

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