Hyperfine Interact (2015) 233:21–27
DOI 10.1007/s10751-015-1154-8

The GBAR antimatter gravity experiment

P. Pérez[1] · D. Banerjee[2] · F. Biraben[3] · D. Brook-Roberge[1] · M. Charlton[4] · P. Cladé[3] · P. Comini[1] · P. Crivelli[2] · O. Dalkarov[5] · P. Debu[1] · A. Douillet[10] · G. Dufour[3] · P. Dupré[6] · S. Eriksson[4] · P. Froelich[7] · P. Grandemange[6] · S. Guellati[3] · R. Guérout[3] · J. M. Heinrich[3] · P.-A. Hervieux[8] · L. Hilico[10] · A. Husson[6] · P. Indelicato[3] · S. Jonsell[9] · J.-P. Karr[10] · K. Khabarova[5] · N. Kolachevsky[5] · N. Kuroda[11] · A. Lambrecht[3] · A. M. M. Leite[1] · L. Liszkay[1] · D. Lunney[6] · N. Madsen[4] · G. Manfredi[8] · B. Mansoulié[1] · Y. Matsuda[11] · A. Mohri[12] · T. Mortensen[6] · Y. Nagashima[13] · V. Nesvizhevsky[14] · F. Nez[3] · C. Regenfus[2] · J.-M. Rey[1] · J.-M. Reymond[1] · S. Reynaud[3] · A. Rubbia[2] · Y. Sacquin[1] · F. Schmidt-Kaler[15] · N. Sillitoe[3] · M. Staszczak[16] · C. I. Szabo-Foster[3] · H. Torii[11] · B. Vallage[1] · M. Valdes[8] · D. P. Van der Werf[4] · A. Voronin[5] · J. Walz[15] · S. Wolf[15] · S. Wronka[16] · Y. Yamazaki[17]

Published online: 21 April 2015

Abstract The GBAR project (Gravitational Behaviour of Anti hydrogen at Rest) at CERN, aims to measure the free fall acceleration of ultracold neutral anti hydrogen atoms in the terrestrial gravitational field. The experiment consists preparing anti hydrogen ions (one antiproton and two positrons) and sympathetically cooling them with Be^+ ions to less than

Proceedings of the International Conference on Exotic Atoms and Related Topics (EXA 2014), Vienna, Austria, 15-19 September 2014

✉ P. Pérez
patrice.perez@cea.fr

1 Institut de Recherches sur les lois Fondamentales de l'Univers, CEA Saclay, F-91191 Gif-sur-Yvette, France

2 Institute for Particle Physics, ETH Zürich, Otto Stern Weg 5, CH-8093 Zürich, Switzerland

3 Laboratoire Kastler Brossel, Collège de France, UPMC-Sorbonne Universités, CNRS, ENS-PSL Research University, Paris, France

4 Department of Physics, Swansea University, Swansea SA2 8PP, UK

5 P. N. Lebedev Physical Institute, 53 Leninsky Prospect, 117924 Moscow, Russia

6 Centre de Sciences Nucléaires et de Sciences de la Matière (CSNSM), CNRS : UMR8609 – IN2P3 – Université, Paris Sud - Paris XI, France

7 Department of Chemistry Ångström, Uppsala University, Box 518, 75120 Uppsala, Sweden

10 μK. The ultracold ions will then be photo-ionized just above threshold, and the free fall time over a known distance measured. We will describe the project, the accuracy that can be reached by standard techniques, and discuss a possible improvement to reduce the vertical velocity spread.

Keywords Antimatter · Gravity · Antihydrogen · Positronium

PACS 04.80.Cc · 07.77.Ka, · 29.25.-t · 41.75.Fr

1 Introduction

The aim of the GBAR experiment at CERN is to measure the free fall of antihydrogen atoms in order to test the Equivalence Principle in a direct way with antimatter. There are already indirect constraints on this subject coming either from matter experiments [1] or from measurements on antiprotons [3]. A direct constraint may be obtained from the arrival times of neutrinos and antineutrinos that were observed from supernova 1987a [4]. However, this result is based on a single event classified at only 90 % CL as having originated from a neutrino interaction, and is not guaranteed to be reproducible in the near future. A first direct experiment was performed by the ALPHA collaboration at CERN [5] that set a constraint on the ratio of the gravitational to inertial mass of antihydrogen to be less than about 100. The first phase of GBAR is to obtain a precision of 1 % on the acceleration of these antiatoms in the terrestrial gravity field. A brief description of the methods and techniques foreseen for this experiment are given below.

[8] Institut de Physique et Chimie des Matériaux de Strasbourg, 23 rue du Loess, F-67037 Strasbourg, France

[9] Department of Physics, Stockholm University, SE-10691 Stockholm, Sweden

[10] Laboratoire Kastler Brossel, Collége de France, Université d'Evry Val d'Essonne, UPMC-Sorbonne Universités, CNRS, ENS-PSL Research University, Paris, France

[11] Institute of Physics, University of Tokyo, 3-8-1 Komaba, Meguro, Tokyo, 153-8902, Japan

[12] Graduate School of Human and Environmental Studies, Kyoto University, Kyoto, Japan

[13] Department of Physics, Tokyo University of Science, 1-3 Kagurazaka, Shinjuku, Tokyo, 162-8601, Japan

[14] Institut Max von Laue - Paul Langevin (ILL), 6 rue Jules Horowitz, F-38042, Grenoble, France

[15] Johannes Gutenberg Universität, D-55128 Mainz, Germany

[16] Narodowe Centrum Badań Jądrowych ul. Andrzeja Sołtana 7, 05-400 Otwock, Świerk, Poland

[17] Atomic Physics Laboratory, RIKEN, 2-1 Hirosawa, Wako, Saitama, 351-0198, Japan

2 Principle of the method

In order to perform a free fall measurement on atoms, it is necessary to obtain very low velocities. While the AEGIS [6] experiment needs to cool antiprotons in order to produce cold antihydrogen atoms after combination with positrons, we chose a different path [7] based on an idea first suggested by Walz and Hänsch [8] that uses an antihydrogen ion, the antimatter counterpart of H^-, i.e. composed of an antiproton and two positrons, that we denote $\overline{H}^+$. A three-body interaction where an antiproton interacts with two positrons efficiently produces the antihydrogen atoms as shown in the already running antihydrogen experiments, although in a highly excited state. For GBAR we will use two charge exchange reactions with positronium (Ps): $\overline{p} + Ps \longrightarrow \overline{H} + e^-$ followed by $\overline{H} + Ps \longrightarrow \overline{H}^+ + e^-$. The first reaction with an antiproton is also a three-body process, but since Ps is a bound state, the cross-section is much higher. The second reaction between the previously produced antiatom and Ps produces the anti-ion. Note also that the binding energy of H^- being 0.75 eV is also the energy level of the third excited state of Ps. We may thus expect an enhancement of the cross section if Ps is excited. These cross-sections have been calculated recently [9], including excitation of Ps, and show that the cross-section is maximal for $\overline{p}$ energies below 6 keV (Fig. 1). Still, given the expected number of around 5 10^6 low energy antiprotons available per burst at CERN, a high density of 10^{12}cm^{-2} Ps is necessary to produce one $\overline{H}^+$. This anti-ion can be sympathetically cooled with laser cooled matter ions such as Be^+ to temperatures of less than 10 μK. Then the extra positron may be photo-detached by a laser pulse, with an energy only a few μeV above threshold, in order to obtain an ultra cold antiatom. The time of flight of the resulting free fall can then be readily measured to extract the acceleration due to the Earth's gravity.

3 Apparatus

The experimental proposal was approved by CERN in 2012 [11]. The different parts of the apparatus that are presently in preparation and their status are briefly described in the following sections. An overall scheme is shown in Fig. 2.

3.1 Antiprotons

The Antiproton Decelerator at CERN currently produces 5 MeV antiprotons. It will be complemented by a decelerator ring called ELENA to bring the antiprotons to 100 keV kinetic energy [12]. We must further decelerate in the range from 1-10 keV in order to optimise production (see Section 2). To this aim, the CSNSM team in Orsay is preparing a system of electrodes that first reduce the energy by applying a high voltage. In order to keep the rest of the apparatus grounded, while the antiprotons traverse a drift tube long enough to contain the pulse, its voltage is quickly dropped using a fast switch (see Fig. 3). However, the emittance of the beam is thus increased by the ratio of the square root of the input to output energies. A set of electrostatic lenses ensures a 30 % efficiency for the beam to pass through a 1 mm x 1 mm x 2 cm tube corresponding to the Ps target geometry, according to simulations.

The dispersion in longitudinal momentum of the antiproton beam from ELENA is too large for an efficient capture of the anti ions. Modifications to the drift tube scheme (see Fig. 3) are under study.

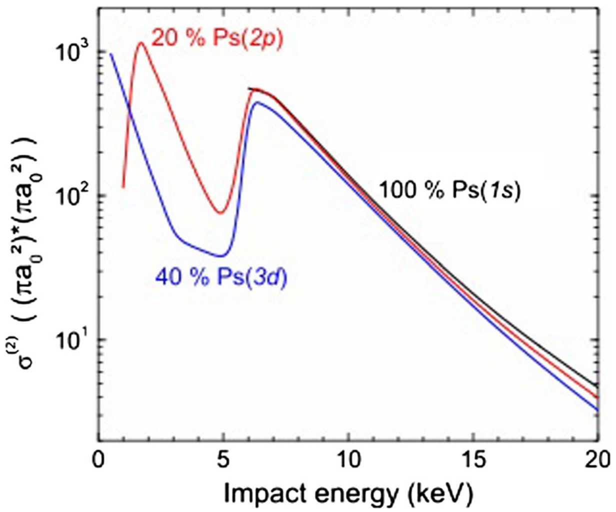


Fig. 1 $\overline{H}^+$ production cross-sections from [9] for $\overline{p}$ impinging on a Ps cloud. The black curve represents the case without Ps excitation. The red and blue curves are for 2P and 3D level excitation that correspond to the 243 or 410 nm lasers in Fig. 2. The 410 nm laser will be used in a 2 photon excitation

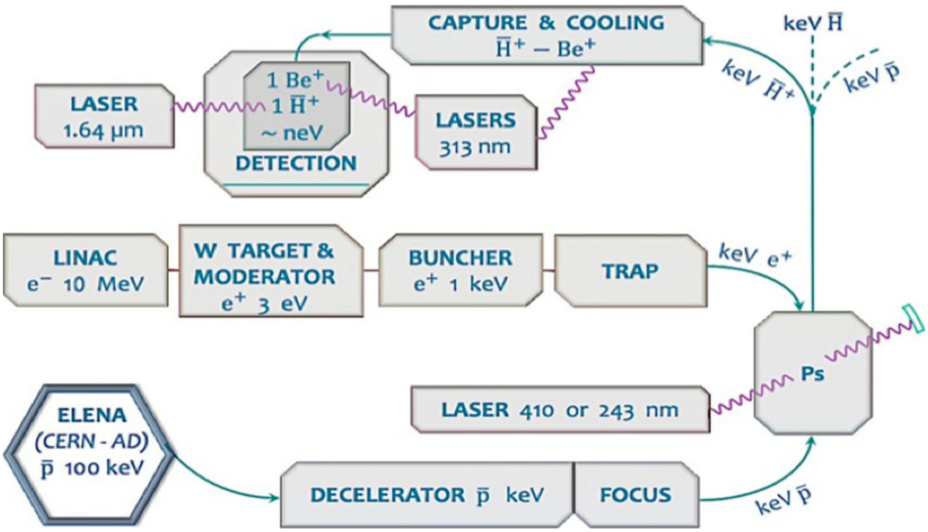


Fig. 2 Overall scheme of the GBAR experiment

3.2 Ps target

The positronium target will be made in the form of a cylinder of 1 mm x 1mm cross section and 2 cm long. The four plates making this cylinder will be coated with a porous silica film developed at Saclay and shown to convert 30 to 40 % of the incident positrons into ortho positronium that return from this surface into vacuum [13]. It was recently shown by Crivelli [15], that a 30 nm thick Si_3N_4 window inserted into one of these plates allows the positrons

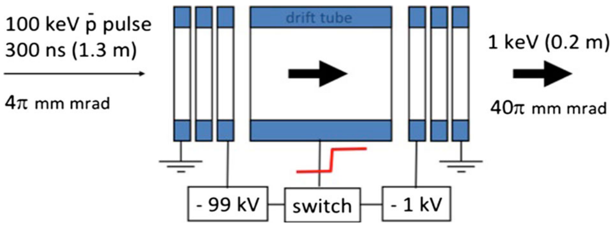


Fig. 3 Sketch of the drift tube for antiproton deceleration

to impinge onto the silica target from the side (see Fig. 4) with no loss if the energy is above a few keV, i.e. in the efficient range to be converted into Ps. The coating has a negative work function for Ps, so that once produced inside the tube it may bounce without being annihilated, thus forming a dense cloud. This cloud can also be excited with laser beams (see Fig. 4). The Kastler-Brossel laboratory (LKB) in Paris has developed a 410 nm two-photon laser system to excite the 3D level of orthopositronium [16], and is preparing also a 243 nm one photon laser to excite the 2P level (see Fig. 1). The 3D laser is presently being used to prepare a fluorescence detector using a Cs vapour to mimic the conditions that will be available with the positronium setup being installed at Saclay.

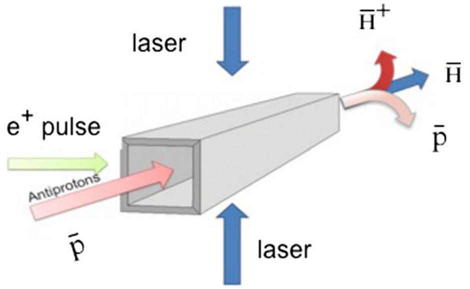
3.3 Positron production and accumulation

In order to produce one anti-ion per ELENA pulse every 110 s, the flux of slow positrons must be $3 \times 10^8 s^{-1}$. For this purpose a 10 MeV electron linac with 0.2 mA average current and repetition rate of 300 Hz will be built by the NCBJ group in Swierck (Poland). Positrons are produced via pair production in a tungsten target and moderated in a tungsten mesh moderator placed close to the primary target. A demonstrator has been setup at Saclay in order to test positron production and accumulation. It consists of a small 4.3 MeV, 0.12 mA accelerator producing 3×10^6 slow e^+s^{-1}. A positron beam line allows transport of the positrons to a Penning-Malmberg trap. The trapping mechanism being tested presently is based on electron cooling rather than the standard Greaves-Surko buffer-gas technique. This technique has been pioneered by N. Oshima at RIKEN with the same trap [17]. In the Saclay setup, we are taking advantage of the pulsed structure of the beam [18] to increase efficiency. First trials showed accumulation only when the preloaded electron plasma is present [19]. Work is going on to increase the accumulation rate.

3.4 $\overline{\mathrm{H}}^+$ trapping and cooling

The anti-ions will keep the kinematic phase space from their parent antiprotons. These have keV energies as well as tens of eV energy spread in the present scheme. Although the task to reach the required neV energies seems formidable, a scheme involving two cooling steps has been outlined [20]. In the first step, the keV antimatter ions are captured in a linear RF trap where they are sympathetically cooled by Coulomb interaction with a laser cooled crystal of more than 10000 Be^+ ions. To avoid photodetachment by the cooling laser light near 313 nm, it is necessary to obtain a short cooling time. Detailed simulations [20] showed that the mechanical coupling between Be^+ and $\overline{\mathrm{H}}^+$ is not optimal with a 9 to 1 mass ratio. Instead, adding HD^+ ions to the Be^+ cloud allows better coupling leading to a cooling time of the order of 1 ms to reach a temperature in the mK range. For the second cooling step,

Fig. 4 Sketch of the Ps target formed of 4 faces internally coated with porous silica and of the directions of incoming and outgoing beams



the $\overline{H}^+$ ions are separated from the Be crystal, extracted and injected in a precision trap to form a Be^+ / $\overline{H}^+$ ion pair on which ground state Raman side band cooling can be performed to the ground state of vibration at the Heisenberg limit $\Delta p \times \Delta x = \hbar/2$. This will be followed by an adiabatic expansion of the trap potential to improve on the momentum uncertainty further, reaching average velocities of $1 ms^{-1}$. The precision trap is being prepared in Mainz University (QUANTUM) where the first tests will be made with $^{40}Ca^+$ and Be^+ ions (mass ratio of 4.4 to 1). The catching trap and first cooling trap are under construction at LKB Paris and will be tested with H_2^+ ions and protons (mass ratios of 9 to 2 and to 1).

3.5 Free fall detection

The vacuum vessel in which the free fall of the neutral atom will take place, after photodetachment of the ion, will be surrounded by a tracking detector. It will serve to reject background events such as cosmic rays. An annihilation event has an average of three charged pions produced with each 0.3 GeV/c. Such particles easily traverse the vacuum chamber vessel and leave straight tracks by ionising the gas of the detector. Reconstruction of these track segments allows determination of the annihilation vertex with a topology much different from that of a typical cosmic ray. The technology envisaged by ETH Zurich for this tracking detector is the so-called bulk microMegas in the form of a set of three double planes of $0.5m \times 0.5m$ dimensions. Five such sets will surround the vacuum vessel. The low event rate also allows multiplexing the readout channels [21].

A cryogenic vacuum environment will lower the pressure such that no residual gas annihilation may take place.

3.6 Vertical velocity selection

The spread of the distribution of the reconstructed acceleration of the antihydrogen atoms will be dominated by the initial velocity dispersion, exceeding 40 % (r.m.s.). In a recent publication [22], some of our collaborators proposed to reduce the initial vertical velocity dispersion by adding two small disks above and below the launch point. The high velocity atoms annihilate on such disks whilst those at lower energies bounce off on them taking advantage of the effect of quantum reflection. Even though the measured event statistics are reduced by a factor 40, the spread of the reconstructed acceleration is lowered to 1.4 % (r.m.s.). In order to obtain the same 1 % precision on the acceleration of antimatter as in the case where no such disks are present, the number of produced $\overline{H}^+$ ions needed is reduced by a factor of 10.

4 Outlook

The GBAR collaboration is now composed of 15 institutes gathering 50 researchers from 8 countries. Installation at CERN should start by the end of 2015 in order to be ready to accept the protons and H^- ions during ELENA commissioning in 2016 and the first run of antiprotons during 2017.

Conflict of interests The authors declare that they have no conflict of interest.

References

1. Adelberger, E.G., et al.: Does antimatter fall with the same acceleration as ordinary matter? Phys. Rev. Lett. **66**, 850–853 (1991)
2. Goldman, T., et al.: Comment on does antimatter fall with the same acceleration as ordinary matter? Phys. Rev. Lett. **67**, 1048 (1991)
3. Gabrielse, G., et al.: Precision mass spectroscopy of the antiproton and proton using simultaneously trapped particles. Phys. Rev. Lett. **82**, 3198 (1999)
4. Pakvasa, S., Simmons, W.A., Weiler, T.J.: Test of equivalence principle for neutrinos and antineutrinos. Phys. Rev. D **39**, 1761 (1989)
5. Amole, C., et al.: Description and first application of a new technique to measure the gravitational mass of antihydrogen. Nat. Commun. **4**, 1785 (2013)
6. Kellerbauer, A., et al.: Proposed antimatter gravity measurement with an Antihydrogen Beam. Nucl. Instr. and Meth. B **266**, 351–356 (2008)
7. Pérez, P., Rosowsky, A.: A New path toward gravity experiments with antihydrogen. Nucl. Instr. Meth. A **545**, 20–30 (2005)
8. Walz, J., Hänsch, T.: A proposal to measure antimatter gravity using ultracold antihydrogen atoms. Gen. Relativ. Gravit. **36**, 561–570 (2004)
9. Comini, P., Hervieux, P.-A.: $\overline{\mathrm{H}}^+$ ion production from collisions between antiprotons and excited positronium: cross sections calculations in the framework of the GBAR experiment. New J. Phys. **15**, 095022 (2013)
10. Comini, P., et al.: $\overline{\mathrm{H}}^+$ production from collisions between positronium and kev antiprotons for GBAR. Hyp. Int. **228**, 159–165 (2014)
11. Chardin, G., et al.: GBAR, Proposal to Measure the Gravitational Behaviour of Antihydrogen at Rest, CERN-SPSC-P-342, 30/09/2011
12. Carli, C.: see proceedings in this conference
13. Cassidy, D.B., et al.: Positronium cooling in porous silica measured via doppler spectroscopy. Phys. Rev. A **81**, 012715 (2010)
14. Crivelli, P., et al.: Measurement of the Ortho-positronium Confinement Energy in Mesoporous Thin Films. Phys. Rev. A **81**, 052703 (2010)
15. Crivelli, P., et al.: Experimental considerations for testing antimatter antigravity using positronium 1S-2S spectroscopy. Int. J. Mod. Phys. Conf. Ser. **30**, 1460257 (2014)
16. Comini, P.: PhD thesis, Université Paris 6, to be published
17. Oshima, N., et al.: New scheme for positron accumulation in ultrahigh vacuum. Phys. Rev. Lett. **93**, 195001 (2004)
18. Dupré, P.: A new scheme to accumulate positrons in a penning-malmberg trap with a linac-based positron pulsed source. AIP Conf. Proc. **1521**, 113 (2013)
19. Grandemange, P., et al.: First results of a new positron-accumulation scheme using an electron linac and a penning-malmberg trap. J. Phys.: Conf. Ser. **505**, 012035 (2014)
20. Hilico, L., et al.: Preparing single ultra-cold antihydrogen atoms for the free-fall in GBAR. Int. J. Mod. Phys: Conf. Ser. **30**, 1460269 (2014)
21. Procureur, S., et al.: Genetic Multiplexing and First Results with a $50 \times 50\mathrm{cm}^2$ Micromegas, NIM A, 729, 888 (2013)
22. Dufour, G., et al.: Shaping the distribution of vertical velocities of antihydrogen in GBAR. Eur. Phys. J. C **74**, 2731 (2014)