

## Towards a gravity measurement on cold antimatter atoms

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**Summary.** — The present status of the AEGIS experiment at CERN (AD-06), on the way of forming anti-hydrogen for a first gravity measurement, is reviewed. Recent results in trapping and cooling positrons and antiprotons in the main electromagnetic traps are presented, including the storage time measurement obtained during the 2014 run with antiprotons, the observation of centrifugal separation of a mixed antiproton/electron plasma and positron accumulation and transfer results obtained during 2015.

## 1. – Introduction

One of the most recent and promising research avenues in physics is the antimatter research community's current effort to exploit achievements in producing and cooling down bunches of more than  $10^7$  antiprotons in the Antiproton Decelerator facility (AD) at CERN to produce significant amounts of thermalized anti-hydrogen atoms. As a result, systematic studies of atomic-physics scale properties of antimatter, such as gravity or atomic spectrum, would become feasible.

Measuring directly gravity on anti-hydrogen to 1% precision is the ambitious objective of the AEGIS collaboration [1]. The measurement scheme chosen by AEGIS is one of the simplest to detect gravity on massive objects, *i.e.* throw horizontally a massive body — in this case, a cloud of anti-hydrogen atoms — and observe its free-fall parabolic trajectory in a constant (Earth's) gravitational field. By measuring the time of flight of the atomic cloud and the vertical displacement using a a moiré deflectometer,  $g$  can be promptly worked out (see [2]).

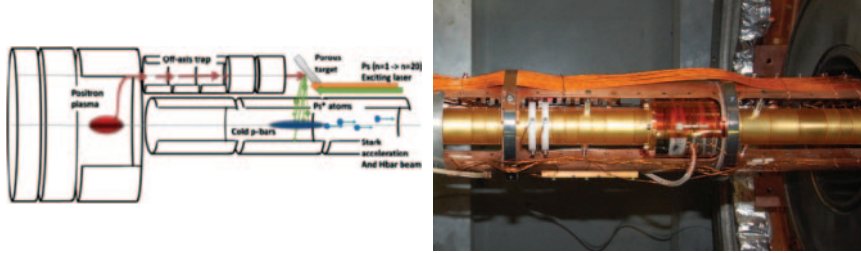


Fig. 1. – Left panel: schematic drawing of AEGIS experimental layout to produce anti-hydrogen by charge exchange with Rydberg-excited positronium. Right panel: a view of the Malmberg-Penning traps used to capture antiprotons and positrons.

## 2. – AEGIS anti-hydrogen production scheme

The scheme chosen by AEGIS to produce anti-hydrogen is positron capture by an antiproton that interacts with a Rydberg-excited Positronium atom, first obtained in [3]. This method, compared to the traditional positron/antiproton plasma mixing (see [4]), shows several advantages. First, being a pulsed scheme, allows to know the time of flight of the formed atoms. Secondly, since antiprotons are not actively moved (by shaping trap potentials) towards a high-density positron plasma, the resulting anti-hydrogen temperature is lower. Finally, the production cross-section grows as the fourth power of the principal quantum number of the positronium atom.

A sketched scheme of the experiment is shown in fig. 1, left panel. A positronium converter made of mesoporous silica placed about 1.7 cm above the anti-hydrogen production trap facing downwards towards the antiproton storage trap. Positrons implanted with keV energy are converted into positronium atoms, which thermalize in the nanochannels and get emitted in vacuum with an overall efficiency of about 9% (see [5]). Two prisms carry two pulses of laser radiation in front of the converter to excite the emitted fraction of P<sub>s</sub> to Rydberg levels, using a two step excitation scheme  $1 \rightarrow 3 \rightarrow n$ , as described in [6]. Rydberg excited positronium survive direct annihilation into gamma rays macroscopic time, allowing the excited atoms to fly towards the antiproton storage trap and perform charge exchange with the cold plasma of antiprotons. A positron plasma is first prepared in a 2.2 cm radius trap, then moved out of the main axis of the experiment by exciting its autoresonant diocotron mode via radiofrequencies (demonstrated with electrons in [7]).

## 3. – Experimental apparatus

AEGIS consists in a cylindrical cryostat containing two sets of cylindrical Malmberg-Penning traps in different magnetic field regions. A first set of traps, in front of the AD beam line, is used to catch and cool antiprotons and positrons in a high magnetic field at 4.5 T (see fig. 1, right panel). After cooling, particles are transferred to a second set of traps in a lower magnetic field region at 1.0 T where the main manipulations described above are performed. Positrons are produced outside the main cryostat on a different beam placed vertically above the AD transfer line by radioactive decay of a  $^{22}\text{Na}$  source. Subsequently, a magnetic buffer-gas accumulator stores the positrons using a well established technique (see [8]). A magnetic transfer line tilted by 45 degrees carries positrons down from the accumulator to the antiproton beam line, so to share the same catching hardware. Antiprotons are sent from AD in bunches of about  $3.0 \cdot 10^7$

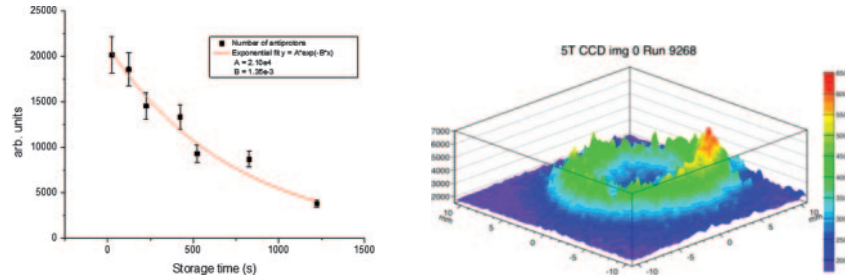


Fig. 2. – Left panel: number of counts on external scintillators after the annihilation of the electron-cooled antiproton fraction, as a function of the storage time. The steepness of the exponential decay curve is a measurement of the vacuum quality within the storage traps. Right panel: image of an antiproton plasma recorded by a microchannel plate detector.

particles every 110 s, with an axial energy of 5.3 MeV. A degrading system made of several  $\mu\text{m}$  thick aluminum foils is used to lower the energy of antiprotons by means of multiple scattering in the degrading material. Subsequently, a Penning-Malmberg trap terminated by high-voltage electrodes captures a fraction of the degraded particles with energies lower than the catching voltage. Antiprotons were trapped by using a 75 cm long Malmberg trap with the final high-voltage electrode set to a constant negative bias and a pulsable high-voltage electrode as entrance endcap.

#### 4. – Antiproton run 2014

The primary goal of the run period of 2014 was to develop and commission the procedures required in forming anti-hydrogen. Trapping conditions of the first commissioning AEGIS run in 2012 were reproduced quickly; a trapping potential of 9 kV was used routinely, which allowed to trap more than  $10^5$  antiprotons/shot. Electron cooling of antiprotons was also reproduced. A plasma of electrons was loaded before capture in the Penning-Malmberg trap by digging a small potential hole in the center of the trap. The source of electrons is the primary current emitted from a thermoelectric filament. Cooling efficiencies close to 90% in about 60 s were routinely obtained, when the electron cloud almost completely overlaps that of the antiprotons.

A critical parameter to the lifetime of cold antiprotons in trap after electron cooling was the pressure of the residual gas in the trap. The vacuum level could not be directly measured with gauges: the best available diagnostics is the lifetime curve itself, since the number of antiproton annihilations per unit second depends on the pressure of the residual gas in the traps (see fig. 2, left panel). The radius of the antiproton plasma was kept monitored by imaging the plasma over a microchannel plate detector, to avoid annihilations on the walls due to the radial enlargement of the cloud.

In fig. 2, right panel, an example of antiproton image on an MCP after electron cooling is shown. Electrons are selectively removed from the trap before the antiproton ejection by using a sequence of fast pulses, with a delay time sufficiently short to be negligible with respect to the characteristic times of the antiproton cloud evolution. Formation of ring structures was reproducibly observed, as expected for a cold two species plasma with different mass at thermal equilibrium in the same trap. This effect, known in the literature as centrifugal separation and observed first for electrons and antiprotons by the ATRAP collaboration [9], is a direct indication that the antiproton plasma has a very

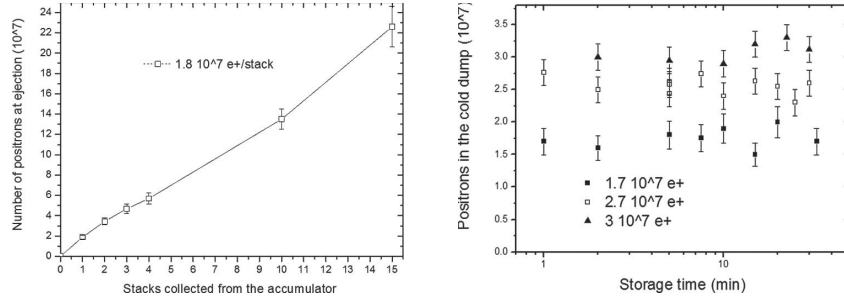


Fig. 3. – Left panel: measurement of positron number stored in the 4.5 T catching traps stacking several shots from the accumulator. Each stack corresponds to around 6 mins of accumulation (2000 pulses from the trap). Right panel: positron plasma lifetime measurement in the 4.5 T catching traps. No loss of positrons has been observed after 30 min of particle storage.

low temperature. For a given electron density  $n$ , the minimal temperature necessary to observe centrifugal separation at a radius  $r$  is given by

$$(1) \quad T_{min} = \frac{m_p e^2}{8k_B \epsilon_0^2} \left( \frac{nr}{B} \right)^2.$$

Measurements obtained with the method of centrifugal separation in 2014 run give a minimum temperature of 10–20 K, in agreement with the environment temperature around the trap region of 10 K.

## 5. – Positron run 2015

Significant progresses in storing and transferring positrons were carried out during 2015. Large number of positrons were collected within the buffer-gas accumulator (as shown in [10]). Positrons were kept accumulating for around 6 minutes, before being transferred to the main catching traps in the 4.5 T region. Losses positron transfer was achieved after optimization of the transfer line parameters: around  $2.5 \cdot 10^7$  positrons were routinely transferred and trapped per shot. Positrons were transferred with a axial velocity corresponding to 300 eV: this energy was dissipated in a fraction of second if the number of positrons transferred exceeded a threshold — experimentally determined — around  $1.3 \cdot 10^7$  positrons per shot. Below this limit, efficient cooling conditions were not found anymore, probably due to the too low density of the plasma. With higher number of positrons, almost 100% cooling efficiency was routinely obtained, and no significant loss due to vacuum was observed, as shown in fig. 3.

In order to reach the reference value of  $10^8$  positrons for anti-hydrogen production, several shots from the accumulator had been collected and stacked into the catching traps. With the current  $^{22}\text{Na}$  source, around 10 mCu of activity at the time of the experiment,  $10^8$  positrons were obtained stacking 8 shots, corresponding to around 45 minutes of accumulation time (see fig. 3). A new, stronger, source of 50 mCu will replace the present source soon, nominally allowing  $10^8$  positrons/shot to be reached in about 8 minutes.

## 6. – Conclusions

AEGIS entered its first data-taking period with both antiprotons and positrons at the beginning of 2015. Significant progresses towards a first experimental demonstration of anti-hydrogen formation for a gravity measurement were obtained in short time. Many goals to produce anti-hydrogen by charge exchange still have to be experimentally demonstrated, from off-axis recapture of the positron plasma to positronium formation in high magnetic field and its laser excitation to Rydberg levels. These goals, together with the spectroscopic studies of positronium carried out in a dedicated environment, constitutes the rich scientific programme of AEGIS for the next years.

## REFERENCES

- [1] KELLERBAUER A. *et al.* (AEGIS COLLABORATION), *Nucl. Instrum. Methods Phys. Res., Sect. B*, **266** (2008) 351.
- [2] AGHION S. *et al.* (AEGIS COLLABORATION), *Nat. Commun.*, **5** (2014) 4538.
- [3] STORRY C. H. *et al.* (ATRAP COLLABORATION), *Phys. Rev. Lett.*, **93** (2004) 263401.
- [4] AMORETTI M. *et al.* (ATHENA COLLABORATION), *Nature*, **419** (2002) 456.
- [5] MARIAZZI S., BETTOTTI P. and BRUSA R. S., *Phys. Rev. Lett.*, **104** (2010) 243401.
- [6] CIALDI S. *et al.*, *Nucl. Instrum. Methods Phys. Res., Sect. B*, **269** (2011) 1527.
- [7] CANALI C. *et al.*, *Eur. Phys. J. D*, **65/3** (2011) 499.
- [8] DANIELSON J. R. *et al.*, *Rev. Mod. Phys.*, **87** (2015) 247.
- [9] GABRIELSE G. *et al.* (ATRAP COLLABORATION), *Phys. Rev. Lett.*, **105** (2010) 213022.
- [10] AGHION S. *et al.* (AEGIS COLLABORATION), *Nucl. Instrum. Methods Phys. Res., Sect. B*, **362** (2015) 86.