PROCEEDINGS OF SCIENCE

# Pulsed Production of Antihydrogen in AEgIS

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Cold antihydrogen atoms are a powerful tool to probe the validity of fundamental physics laws, and it's clear that colder atoms, generally speaking, allow an increased level of precision.
After the first production of cold antihydrogen ($\bar{H}$) in 2002 [1], experimental efforts have progressed continuously (trapping [2], beam formation [3], spectroscopy [4, 5]), with competitive results already achieved by adapting to cold antiatoms techniques previously well developed for ordinary atoms. Unfortunately, the number of $\bar{H}$ atoms that can be produced in dedicated experiments is many orders of magnitude smaller than available hydrogen atoms, which are at hand in large amount, so the development of novel techniques that allow the production of $\bar{H}$ with well defined conditions (and possibly control its formation time and energy levels) is essential to improve the sensitivity of the methods applied by the different experiments.
We present here the first experimental results concerning the production of $\bar{H}$ in a pulsed mode where the time when 90% of the atoms are produced is known with an uncertainty of around 250 ns [6]. The pulsed $\bar{H}$ source is generated by the charge-exchange reaction between Rydberg positronium atoms ($Ps$) and trapped antiprotons ($\bar{p}$), cooled and manipulated in an electromagnetic trap:

$$\bar{p} + Ps^* \rightarrow \bar{H}^* + e^-$$

where Rydberg positronium atoms, in turn, are produced through the implantation of a pulsed positron beam into a mesoporous silica target, and are excited by two subsequent laser pulses, the first to $n = 3$, the second to the needed Rydberg level ($n \simeq 17$).
The pulsed production allows the control of the antihydrogen temperature, and facilitates the tunability of the Rydberg states, their de-excitation by pulsed lasers and the manipulation through electric field gradients.
In fact, the production of pulsed antihydrogen is a major milestone in the AEgIS experiment to perform direct measurements of the validity of the Weak Equivalence Principle for antimatter.

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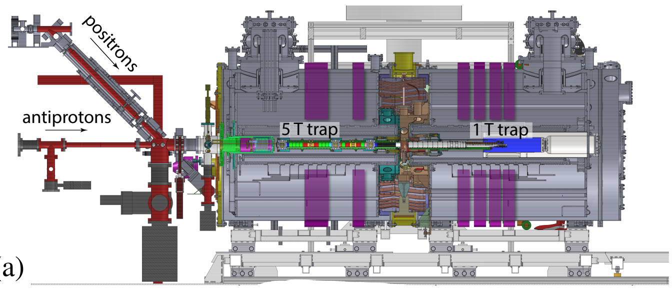
## 1. Introduction

It is experimentally well known that objects fall in the gravitational field of the Earth, at the same location, with the same acceleration whatever is their mass and composition. As a matter of fact, already Newton, in his Philosophiae Naturalis Principia Mathematica [7], stated that inertial and gravitational masses must be the same: this equivalence is nowadays known as Weak Equivalence Principle (WEP). In 1916 Einstein extended the WEP to postulate the Einstein Equivalence Principle (EEP), which is a pillar of the General Relativity [8]. In his formulation of the equivalence principle, Einstein demanded the validity of the WEP as a necessary condition.

Today the WEP has been extensively tested experimentally and very strong limits on its possible violation with ordinary matter have been set [9]. In spite of the fact that some experimental and theoretical arguments suggest that the WEP should also hold for antimatter (see [10] for a comprehensive review), they are indirect and depend on some theoretical assumptions. On the other hand, most of the attempts for a quantum theory of gravity predict new interactions which could violate the WEP for antimatter [11].

The AEgIS experiment goal is to perform a direct test of the WEP on antimatter by the measure of the $g$-acceleration of a cold antihydrogen beam in the Earth's gravitational field, and its development is founded on the idea to measure the vertical displacement, due to gravity, of a beam of antihydrogen passing through a moiré deflectometer coupled to a position sensitive detector, like in [12]. In the following section an overview of the AEgIS experiment and method is reported.



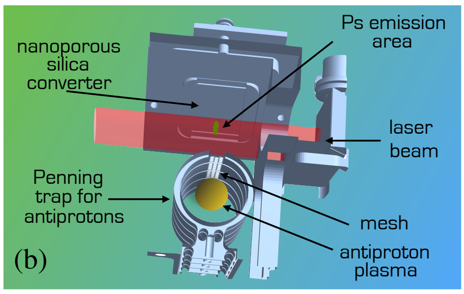




**Figure 1:** (a): Drawing of the experimental apparatus. In violet, the external scintillator detector array. (b): Enlargement of the $\bar{H}$ production region, located in the centre of the 1 T trap.

## 2. Experimental Apparatus and Method

Figure 1a depicts the apparatus of the AEgIS experiment. Its building blocks consist of a ~4.5 T and a ~1 T superconducting solenoids, where a system of Malmberg-Penning traps are accommodated. Once every ~100 s, the CERN Antiproton Decelerator (AD) provides a bunch of antiprotons ($\sim 3 \cdot 10^7$ $\bar{p}$ with 5.3 MeV kinetic energy), which are slowed down through a set of thin aluminum foils (the so-called degrader) and eventually caught through high voltage electrodes in the 4.5 T trap. Antiprotons are then cooled with sympathetic electron cooling, compressed [13] and transferred to the 1 T trap for the $\bar{H}$ production (Figure 1b). While antiprotons are prepared in the above-mentioned way, positrons ($e^+$) are stacked in a Surko-type accumulator based on a ~ 1 GBq $^{22}$Na source. At some point, when the antiprotons are ready, the positrons are released and a pulse of positrons is launched to the positron-positronium converter, a cryogenic, nanoporous target [17] which is situated close to the 1 T antiproton trap (see Figure 1b). The formed positronium or, to be more precise, ortho-positronium (which is the only one living long enough to escape the target), is subsequently excited to a Rydberg state with principal quantum number $n \simeq 17$ through two consecutive laser pulses [18, 19] (the first to $n = 3$; the second to the desired $n$, with an alternative scheme to the one reported in the pioneering work [20]).

This makes some Rydberg $Ps^*$ reach the cold (currently, some hundreds of K) antiproton plasma and give birth to the mentioned resonant charge-exchange process ([14, 15]), that in principle will result in a pulsed antihydrogen production.

In fact, compared with the previous, groundbreaking work where antihydrogen was created through a similar charge-exchange reaction [21], the main advantage of AEgiS method consists in the possibility to create a pulsed antihydrogen beam (derived from a pulsed $Ps$ production). Other advantages are the high cross-section (proportional to $n^4$, where $n$ is the $Ps$ principal quantum number, in the velocity range concerned here - see e.g. [16] and the references therein) and the production of Rydberg $\bar{H}^*$ atoms, that may be accelerated by electric field gradients (thanks to their large electric dipole moment) in order to create a beam.

## 3. Results

The detection of the events discussed here was performed with the so-called "external scintillator detector array" (see Figure 1a), situated outside the superconducting solenoids. What is actually recorded is any event where the signal, conveniently averaged between the 2 photomultipliers (PMTs) reading the same scintillating slab, is above a well-defined threshold. After an accurate calibration of each PMT, the signal amplitude could be considered an excellent proxy for the energy deposit inside the scintillator by the charged particles crossing it, as described in detail in [22], so different efficiencies are expected for antiproton annihilations, $Ps$ annihilations and cosmic/environmental background. A digital acquisition of the full PMT signal, together with an a-posteriori threshold optimization, guided also by a detailed Monte Carlo simulation of the system based on Geant4, allowed us to increase the signal over background ratio for $\bar{p}$ annihilation, which in turn is a signature for $\bar{H}$ annihilation.

In the data taking, we have performed sequences of runs consisting in $\bar{H}$ production cycles with $e^+$ injection, subsequent $Ps$ production and laser excitation in nominal conditions (Figure 2a), cycles without extracting $e^+$ from the accumulator (Figure 2b) and cycles without firing the laser (Figure 2c). The full signal was acquired for a 650 $\mu s$-long time window, starting 50 $\mu s$ before the laser shot ($t = 0$), in order to have a convenient control time window. Unfortunately, the first 1 $\mu s$ after $t = 0$ the detector was blind because it needed to recover from the saturation experienced right after the positron bunch injection, which produced a large number of simultaneous $e^+$ annihilations.

From Figure 2 it is clear that there is a signal when all the three necessary ingredients were present, compared with the other two cases, so being consistent with $\bar{H}$. This signal occurs between $t = 1$ $\mu s$ and $t = 26$ $\mu s$, with some excess events (but significantly fewer) also in the runs with $\bar{p}$ and the laser but without $e^+$ injection, meaning that probably there is also a background of $\bar{p}$

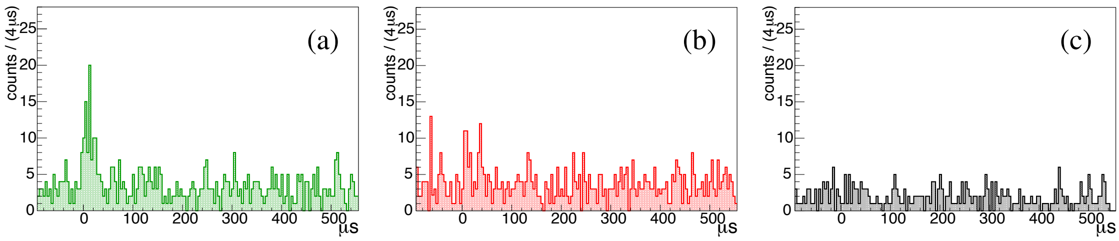



**Figure 2:** Time distribution scintillator pulses. (a): Cycles with $\bar{p}$, $e^+$ and laser. (b): Cycles with $\bar{p}$, laser but without $e^+$. (c): Cycles with $\bar{p}$, $e^+$ but without laser. The overall number of cycles is around a few thousands for each typology of data, and differs (but by less than a factor of 2) between the three options, so histogram renormalization is applied.

annihilations due to laser-induced outgassing from the cryogenic surfaces. Performing a more detailed statistical analysis, outlined in the main paper [6], we have found that the null hypothesis of the absence of signal is rejected with 4.8 $\sigma$ (local significance).

## 4. Conclusions

We have presented the first AEgIS results about $\bar{H}$ pulsed production, that is the one with the most precise time tagging reached till now. It relies on the charge exchange reaction between laser-excited $Ps^*$ and $\bar{p}$. The main obstacle now is that the production rate is extremely low: on average, less than 0.1 $\bar{H}$ for a typical cycle performed in 2018. In fact, for the future, substantial improvements should be carried out to increase the number of $e^+$, and then of $Ps^*$, available at each cycle, and independently the number of trapped $\bar{p}$, the latter thanks to the ELENA/AD upgrade. Even the converter/trap system may be further refined to reduce the number of lost $Ps^*$, as well as to increase the low-temperature $Ps^*$ component, whose cross section is much larger. On the other hand, it should be noted the annihilation time distribution of the $\bar{H}$ is slightly surprising, since we observe also events at more delayed times than expected, and this certainly needs further investigation.

The subsequent steps, made possible by this first evidence, will include the pulsed formation of a beam by Stark acceleration with inhomogeneous electric fields (laser de-excitation towards the fundamental state may be needed, followed by re-excitation to another defined Rydberg state). This will allow high-precision hyperfine splitting measurements, the production of a pulsed, horizontally traveling atomic beam, or even an efficient $\bar{H}$ transport through electric/magnetic field gradients.

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