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The AEgIS experiment: towards antimatter gravity measurements

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Abstract. AE$\bar{\text{g}}$IS (Antimatter Experiment: Gravity, Interferometry, Spectroscopy) is a CERN based experiment aiming to probe the Weak Equivalence Principle of General Relativity with antimatter by studying free fall of antihydrogen in the Earth's gravitational field. A pulsed cold beam of antihydrogen produced by charge exchange between Rydberg positronium and cold antiprotons will be horizontally accelerated by an electric field gradient. The free fall of antihydrogen will then be measured by a classical moiré deflectometer. An overview of the experimental setup, present status of the experiment along with current achievements and results is presented.

1. Introduction

The reason for the observable universe appearing to consist of practically only matter with an unexplained absence of antimatter is still unknown. Experiments based at CERN's Antiproton Decelerator (AD) [1] are attempting to tackle this puzzle by chasing asymmetrical properties between hydrogen and antihydrogen ($\overline{\mathbf{H}}$), its antimatter counterpart. The Weak Equivalence Principle (WEP), which postulates that the effect of a gravitational field on a system does not depend on its composition or structure [2] has been extensively tested to a precision of 1.8×10^{-15} with ordinary matter [3], but not with antimatter so far. In 2002, the ATHENA experiment created cold antihydrogen [4] via a three-body recombination by mixing trapped antiprotons with positrons at low energies. This achievement opened the possibility to test WEP on neutral antimatter since it is not sensitive to stray electric and magnetic fields.

The AE$\bar{\text{g}}$IS experiment primary scientific goal is the direct measurement of the Earth's gravitational acceleration on antihydrogen [5] by observing the vertical displacement of the shadow image produced by the passage of an $\overline{\mathbf{H}}$ beam through a moiré deflectometer [6]. In order to measure the time of flight of each atom, pulsed production of $\overline{\mathbf{H}}$ atoms is required. The antihydrogen formation scheme chosen by AE$\bar{\text{g}}$IS is based on a charge-exchange reaction between cold trapped antiprotons ($\bar{\text{p}}$) and laser excited Rydberg Positronium (Ps) atoms:

$$Ps^* + \bar{p} \rightarrow \bar{H}^* + e^- \tag{1}$$

which feasibility was initially demonstrated by the ATRAP collaboration [7]. This production scheme is likely to be more efficient than the traditional mixing one (e.g. [4]) since the charge-exchange reaction cross section scales with the fourth power of the Ps principal quantum number. Moreover, it presents the additional advantage of the final antihydrogen quantum states being fully determined by the initial Ps* ones with relatively narrow distribution, allowing them to be accelerated by electric field gradients.

In this paper, the current progress towards cold antihydrogen formation will be reported.

2. The AE$\bar{\text{g}}$IS experimental apparatus

The AE$\bar{\text{g}}$IS apparatus implements two cylindrical cryostats containing 5T and a 1T superconducting magnets, which surround the initial antiproton trapping and the $\bar{\text{H}}$ formation region, respectively. A series of cylindrical electrodes inside each magnet forms a Malmberg-Penning trap arrangement and allows radial and axial confinement of the charged particles. A bunch of 3×10^7 $\bar{p}$ with 5.3 MeV initial kinetic energies is delivered from the AD every 110 s. After being slowed down to a few keV by passing through a set of aluminum foils (degraders) $\bar{p}$ are trapped within the 75 cm long set of Malmberg-Penning traps in the 5 T magnet. Trapped $\bar{p}$ are cooled to a few K by sympathetic cooling with electron cloud previously stored inside the trap. The antiprotons are then ballistically transferred from the 5 T trap system to the 1 T antihydrogen production region, where they are re-caught in flight with an efficiency around 80%. The ballistic transfer combines the advantages of the efficient $\bar{p}$ compression in the 5 T region with low expansion during the multistep procedure. Given that the $\bar{H}$ formation region sited in the 1 T magnetic field must be in close proximity to the Ps source to maximize the solid angle of useful Rydberg Ps, the production trap electrodes radius is only 5mm with an entrance grid on top to allow the passage of Ps* inside the trap. Thus, minimizing the $\bar{p}$ radial dimensions prior to the production trap transfer is of paramount importance. AE$\bar{g}$IS recent advances of the mixed $\bar{p}$ and e^- plasma compression to sub-millimetre radii [8] allowed high $\bar{p}$ densities $n_{\bar{p}} \sim 10^{13}\ \mathrm{m}^{-3}$ to be achieved.

Significant progress regarding positrons (e^+) and Positronium handling was carried out during the last two years. Positrons are produced from a ^{22}Na radioactive source coupled to a Ne moderator, cooled in a two stage Surko buffer trap and stored in a Penning-Malmberg accumulator up to several minutes [9]. The positron cloud ($\sim 10^7$ e^+) is extracted from the accumulator with around 300 eV energy and 20 ns time duration, then guided through a transfer line towards the positronium production target following off-axis trajectories without being re-caught in the 5T traps. The formation of low energy Ps requires to implant e^+ in the Ps converter made of nano-channeled mesoporous silicon [10] deeply enough to allow the formed Ps to have time to cool down by collisions with the channel walls. This highly efficient ground state Ps atoms production [11] is achieved by implanting e^+ in the converter with few keV energy. In the AE$\bar{g}$IS framework the acceleration is performed during the e^+ passage through the transfer line by the "kicker": a single cylindrical electrode mounted along the transfer line, which could be quickly (few nanoseconds risetime) pulsed up to 5 kV.

The final important step towards pulsed $\bar{H}$ beam formation is the excitation of Ps atoms into Rydberg states by using the two-photon excitation scheme developed in the AE$\bar{g}$IS collaboration [12]. An UV (205.045 nm) laser pulse excites Ps to n=3, while an infrared (1680-1720 nm) laser pulse brings the atoms to Rydberg states varying from n=15 to n=20 [13]. Rydberg Ps* lifetime being much higher than in the ground state (tens of μs/ms instead of 142 ns) allows the Ps* atoms to reach the $\bar{p}$ production trap without annihilating in flight. The two laser pulses are sent at grazing angle on the Ps converter (see figure 1, laser is shining perpendicularly to the figure plane) synchronously and with tunable delay with respect to the e^+ implantation moment.

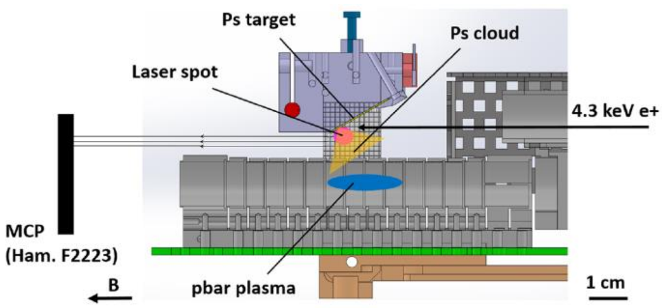

Figure 1. Antihydrogen production region.

The commonly used technique to study Ps formation and its excitation is the Single-Shot Positron Annihilation Lifetime Spectroscopy (SSPALS) [13], [14] which consists in collecting the gamma rays emitted by annihilation of positrons with nanosecond time resolution. This technique has some limitations in application to Ps laser excitation in the AE$\bar{g}$IS experimental apparatus geometry, which is not allowing for an efficient collection of the gamma rays produced by positron annihilation. The free space in Ps converter vicinity being limited prevents long life time states to be revealed in the SSPALS spectrum. This challenge became a driving force for the development of an alternative diagnostic for the Ps laser excitation, based on a MCP detector imaging the charged e^+ produced from the Ps photo or self-ionization and being guided by 1 T magnetic field. The dissociated e^+ and e^- being confined to their magnetic field lines are guided to the front face of the MCP polarized accordingly. The most significant advantage is that this technique, when used to image photopositrons, is background free due to absence of any other source of positively charged particles.

3. Conclusion

The recent advances achieved regarding Positronium formation in cryogenic environment, its Rydberg laser excitation and antiproton manipulation have been reported. A new diagnostic technique of Ps Rydberg excitation for pulsed antihydrogen production based on MCP detector developed recently has been highlighted.

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