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Weighing antimatter: AE$\bar{\text{g}}$IS Phase 2, upgrades and first data

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Summary. — AE$\bar{\text{g}}$IS (Antimatter Experiment: Gravity, Interferometry, Spectroscopy) is an experiment at the Antiproton Decelerator (AD) facility at CERN whose goal is to study the asymmetry between matter and antimatter and, in particular, the effect of the Earth's gravitational field on antihydrogen ($\bar{\text{H}}$). During the 2018 run, $\bar{\text{H}}$ was formed, leading into considerable gain of knowledge on the processes involved. Therefore, in the last two years, during CERN LS2, multiple upgrades to the experiment have been carried out, spanning from new degraders, a new $\bar{\text{H}}$ formation trap scheme, an entirely new control system, a more efficient positronium (Ps) converter, and more efficient sensors. All this work is necessary towards the goal of creating the first pulsed beam of neutral $\bar{\text{H}}$, which will enable inertial studies on antihydrogen with high degrees of precision. This contribution presents different upgrades, their validation with the antiprotons beam, and the further developments foreseen in the future.

1. – Introduction

The rarity of antimatter in the observable universe is a long-standing problem for physicists, as the Standard Model predicts that equal amounts of matter and antimatter should have been produced during the Big Bang. A candidate explanation for this asymmetry is a difference in the gravitational coupling of matter and antimatter, which would lead to a violation of the Weak Equivalence Principle. Some theories beyond the Standard Model predict such a difference [1].

The main goal of AE$\bar{\text{g}}$IS (Antimatter Experiment: gravity, Interferometry, Spectroscopy) is to determine the gravitational acceleration of antimatter in the Earth's gravitational field. The methodology is to produce a time-defined, pulsed beam of antihydrogen atoms, and let it fall while travelling inside the grates of a Moiré deflectometer: the gravitational fall can be deduced from the interference pattern seen on the detector.

2. – AE$\bar{\text{g}}$IS Phase 1: first antihydrogen in AE$\bar{\text{g}}$IS

The aim of the Phase 1 of AE$\bar{\text{g}}$IS was to demonstrate the use of the charge-exchange reaction to pulse-produce $\bar{\text{H}}$ with $\bar{\text{p}}$ from the Antimatter Decelerator and Rydberg (Ps) atoms. The incoming antiprotons were slowed from 5.3 Mev to below 10 keV by utilising a material degrader, and subsequently trapped and cooled in a Penning trap, by using

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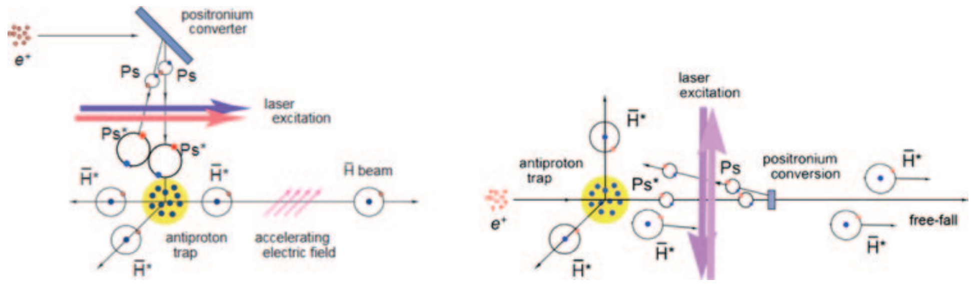

Fig. 1. – Left: orthogonal formation scheme, where the Ps illuminates the $\bar{p}$ perpendicularly. Right: collinear formation scheme, minimising Ps ionisation caused by the motional Stark effect.

simultaneously sympathetic cooling with e^- and by compressing the $\bar{p}$ plasma with the rotating wall technique. Subsequently, a beam of keV e^+ was directed onto a nano-channelled silica porous e^+-PS converter, producing a cloud of Ps moving perpendicularly towards the $\bar{p}$ plasma. The Ps were brought to $n_{Ps} = 17$ via a two-step laser excitation. The formation of antihydrogen was demonstrated by the difference in annihilation rates on a scintillating detector when using antiprotons, positrons and laser simultaneously, corresponding to a production rate of 0.05 $\bar{\mathrm{H}}$ per cycle of the experiment (about 110 s).

This $\bar{\mathrm{H}}$ production scheme has several advantages: the production is pulsed and well defined in time (~ 250 ns uncertainty), enabling precise time-of flight analyses; the resulting $\bar{\mathrm{H}}$ temperature is defined by the $\bar{p}$ one, resulting in cold formation; and the reaction cross-section scales rapidly with n_{Ps}, being $\sigma \propto n_{Ps}^4$. AE$\bar{g}$IS Phase 1 was concluded successfully in 2018, with the pulsed formation of cold $\bar{\mathrm{H}}$ in the trap [2]. A key enabler for this result has been the excitation of Ps to $n_{Ps} = 17$ in a highly magnetic field (1 T) [3].

3. – AE$\bar{g}$IS Phase 2: the upgrade

AE$\bar{g}$IS Phase 2 aims to consolidate and improve the antihydrogen formation process, while testing the first proof-of-concept inertial measurement with antimatter. The outcome of the Phase 1 campaign was, indeed, that an increase of 2–3 order of magnitude of $\bar{\mathrm{H}}$ production is needed (to arrive to 1–10 $\bar{\mathrm{H}}$ per cycle) to obtain the necessary statistic for a gravity measurement with a final precision in the order of 1%. Moreover, $\bar{p}$'s (and hence $\bar{\mathrm{H}}$'s) need to be cooled down to tenths of kelvin, an order of magnitude more than the $\sim$400 K reached before. The other two milestones for the Phase 2 (which will end in 2025, with the start of CERN LS3) are to form a forward-boosted antihydrogen beam, and to construct and test a prototype of the Moiré Deflectometer for inertial measurement.

The most relevant modification is the improved $\bar{\mathrm{H}}$ formation scheme (see fig. 1). Now the e^+-PS target is positioned along the axis of the trap, so that the Ps produced travels towards the $\bar{p}$ plasma collinearly to the magnetic field. This raises the limit n_{Ps}^{max} from 19 to 32, being imposed by the Ps ionisation due to the motional Stark effect ($n_{Ps}^{max} \propto \theta^{-1/4}$). This should give a 16-fold increase in $\bar{\mathrm{H}}$ production cross-section.

The revised formation scheme made necessary to redesign the formation trap, which was assembled and installed in 2022. The new trap has bigger and fully circular electrodes, with two-stage electrical noise filtering, to improve $\bar{p}$ plasma stability and lifetime. It is also more than 20 cm shorter, to gain space so that the $\bar{\mathrm{H}}$ gravity sensor can be placed into a magnetic-field homogeneous section of the experiment. Moreover, the entire trap can be precisely aligned to the magnetic field axis thanks to cryogenic motors.

In addition, from 2021, the antiprotons are fed to the experiments from ELENA (Extra Low Energy Antiproton ring) [4], a further deceleration stage that brings the particles' energy from 5.3 Mev down to 100 keV, delivering them in bunches of $\sim 5 \times 10^6$ $\bar{\text{p}}$'s every 2 min, simultaneously to up to 4 experiments. New degraders have been developed, in order to maximise the amount of $\bar{\text{p}}$'s transmitted with an energy lower than 10 keV, the maximum amount trappable by our catching trap. This combination should correspond to at least 50 times more $\bar{\text{p}}$'s trappable per cycle with respect to 2018, which will reflect into a higher $\bar{\text{H}}$ yield.

The introduction of ELENA has also brought a dramatic shift in operation modality. In fact, if before it was possible to run the experiment with the constant monitor of multiple experts during data-taking shifts of 8 h/day, the current continuous beam delivery would demand a workload unsustainable for the operators. Therefore, a paradigmatic change has taken place, from a software infrastructure of various independent subsystems on different machines, to a new common control system framework, called TALOS (Total Automation of LabVIEW$^{\text{TM}}$ Operations for Science). TALOS unifies all the individual control programs in a unique, coordinated distributed environment, and enhances its reliability and safety through a distributed watchdog system: it ensures that no single component can become unresponsive without detection. These characteristics are crucial for the full automation of experimental procedures, as high-level decisions often depend on parameters generated by multiple computers, and allow for extended periods of unmanned operation. In addition, the entire code is divided into modular, independent components with a clear scope and task, which operate asynchronously and interact with one another through a built-in messaging system. It is written in LabVIEW$^{\text{TM}}$, using the structure of the Actor Model [5].

In parallel, the previous custom-made control electronics has been migrated to a new one based on ARTIQ/Sinara [6], an open hardware & software ecosystem expressly created for quantum physics experiments. The combination of the modularity and the ns synchronisation capability of the hardware, and the easiness of programming given by ARTIQ, based on Python, has streamlined the operations on the experiment, and further improved their timing accuracy.

Last but not least, improvements to the Ps system are also important. A study has been performed to optimise the efficiency of the e^+-PS silica target by fine-tuning the morphology of the nano-channel. Together with the possibility of baking the target in the trap, during cryogenic conditions, the Ps conversion should be enhanced five times.

4. – First measurements

During the antiprotons data-taking campaign of 2021, the primary objective was to validate the functionality of the new subsystems. The performance of the new degraders was demonstrated by gating the passage of the moderated $\bar{\text{p}}$'s with the 10 kV electrode of the catching trap, detecting the difference with the new microchannel plate (MCP) at the end of the trap and the scintillators around it. The 1600 nm parylene degrader showed a $\sim$15% of transmitted $\bar{\text{p}}$'s with $E <$10 keV, which where promptly caught for several seconds (see fig. 2). Subsequently, a study of the correlation of the time of flight of $\bar{\text{p}}$'s with their energy was performed, and the energy profile of the trapped $\bar{\text{p}}$'s was characterised. Conjointly, these achievements demonstrated the capability of the upgraded control system electronics and software, by running the experiment unsupervised at all

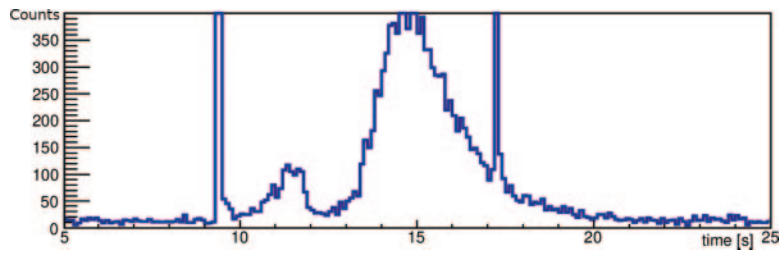

Fig. 2. – The structure in-between the two deltoids peaks (ELENA $\bar{\mathrm{p}}$ ejection and trap opening) is the annihilation of the trapped $\bar{\mathrm{p}}$ with the non-perfect vacuum.

nights during data-taking, automatically handling errors and acting accordingly.

5. – Conclusions and future development

In the first years of the AEḡIS Phase 2, the experiment's apparatus underwent multiple upgrades, from a new formation trap, a better e^+-PS target, to a completely new control system electronics and software. All these modifications showed a highly improved system, paving the way, in the next years, for the pulsed formation of 1–10 $\bar{\mathrm{H}}$ atoms per 110 s cycle of ELENA, with a temperature of tenths of kelvin. A pulsed beam of antihydrogen will be formed by imparting momentum along the trap axis to the $\bar{\mathrm{p}}$'s, during the transfer from the catching trap to the formation trap. In turn, this will enable performing the first inertial measurement on $\bar{\mathrm{H}}$ with the Moiré Deflectometer in development, to be placed in the space liberated by the new, shorter trap.

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REFERENCES

[1] Nieto M. and Goldman T., *Phys. Rep.*, **205** (1992) 221.
[2] AEḡIS Collaboration (Aghion S. *et al.*), *Nat Commun. Phys.*, **4** (2021) 19.
[3] AEḡIS Collaboration (Antonello M. *et al.*), *Phys. Rev. A*, **102** (2020) 013101.
[4] Chohan V. *et al.*, *Extra Low Energy Antiproton ring (ELENA) and its Transfer Lines, Design Report*, CERN-2014-002 (2014).
[5] Hewitt C., Bishop P. and Steiger R., *A universal modular ACTOR formalism for artificial intelligence*, *IJCAI '73: Proceedings of the International Joint Conference on Artificial Intelligence* (IJCAI) 1973, pp. 235–245.
[6] Kasprowicz G. *et al.*, *ARTIQ and Sinara: Open Software and Hardware Stacks for Quantum Physics*, *OSA Quantum 2.0 Conference* (Optical Society of America) 2020, p. QTu8B.14.