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ELENA: Bright Perspectives for Low Energy Antiproton Physics

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ELENA: Bright Perspectives for Low Energy Antiproton Physics

Introduction

Although incredibly successful, the standard model of particle physics (SM) is known to be glaringly incomplete. For example, it has so far failed in the unification of all known forces, and it includes 19 free parameters that have to be determined by experiments, indications of the phenomenological nature and incompleteness of the theory. Some great triumphs of the SM are the prediction of the Higgs boson and its detection, or the prediction and detection of the exchange quanta of the weak interaction. Another great achievement is the precise calculation of the electron's anomalous magnetic dipole moment, which results in the most precise quantum-electrodynamics-based determination of the fine structure constant.

Frustratingly, the success of the SM is restricted to the description of not more than 5% of the energy content of our universe, and even the fundamental mechanisms to explain how this small fraction came into stable existence have yet to be understood. Combining the Λ-Cold Dark Matter (Λ-CDM) model and the SM, we would expect to find a radiative universe with a baryon/antibaryon ratio of ≈ 1, and a baryon/photon ratio of 10^{-18}. Astrophysical observations indicate on the other hand an experimental baryon/photon ratio of $\sim 6 \times 10^{-10}$, challenging our current best understanding by a theory/experiment disagreement of almost nine orders of magnitude. A possible explanation for this discrepancy would be an asymmetry between matter and antimatter that has yet to be discovered.

This inspires experiments, such as the ones operated at the Antiproton Decelerator (AD)/Extra Low ENergy Antiproton (ELENA) facility of the European Council for Nuclear Research (CERN), that compare the fundamental properties of stable matter/antimatter conjugates at low energies and with great precision. In recent years, the user community at the AD invented a plethora of cutting edge technologies (see the illustrations in Figure 1), culminating in comparisons of the proton-to-antiproton charge-to-mass ratio with a fractional accuracy of 16 parts in a trillion [1], a >1,000-fold improved test of charge, parity, time reversal invariance by measuring the proton and antiproton magnetic moments with parts per billion precision [2], and by measuring an atomic transition in antihydrogen ($\bar{H}$) with a fractional accuracy of 2 parts in a trillion [3, 4]. In addition to those tests of CPT invariance, the AD/ELENA physics program is currently being extended by experiments that test the free-fall weak equivalence principle through the investigation of the ballistic behavior of $\bar{H}$ atoms in the gravitational field of Earth [5–7], and by new experiments that rely on the implementation of transportable antiproton traps [8].

Thanks to the strong support of CERN to further extend the sensitivity and reach of its antimatter program, the new extra low energy deceleration synchrotron ELENA (see Figure 1), has recently been implemented into the AD facility, with the potential to drastically enhance the facility's performance and provide much improved beam quality.

Currently, six collaborations are active within the AD/ELENA facility (see Figure 2): AEgIS [9], ALPHA [3], ASACUSA [10, 11], BASE [12], GBAR [6], and PUMA [8].

One of the common workhorses of those experiments is a device called a Penning trap, which is used for trapping charged particles, either for single-particle studies or formation of $\bar{H}$ atoms (see Figure 3).

AEgIS, GBAR, and a part of the ALPHA collaboration are testing the weak equivalence principle by investigating the ballistic behavior of $\bar{H}$ in the gravitational field of Earth. The ASACUSA collaboration is focusing on tests of CPT invariance by ground-state-hyperfine spectroscopy in a beam of polarized $\bar{H}$ atoms produced in a CUSP trap [11]. Using a hydrogen beam to commission their spectroscopy apparatus, the collaboration has measured the ground state hyperfine transition frequency $\nu_{\mathrm{GSHFS}} = 1\ 420\ 405\ 748.4(3.4)(1.6)$ Hz, which has a fractional precision of 2.7 p.p.b., and constitutes the most precise measurement of this quantity in a beam apparatus [14]. Another initiative within ASACUSA is performing high-resolution spectroscopy of the exotic atom antiprotonic helium [10], in which one of the electrons in the He shell is replaced by an antiproton. Laser spectroscopy on this three-body system gives access to the antiproton-to-electron mass ratio $m_{\bar{p}}/m_{\mathrm{e}}$. Using buffer-gas-cooled antiprotonic helium atoms at a temperature of $\approx 1.6(1)$ K, ASACUSA managed to determine the ratio $m_{\bar{p}}/m_{\mathrm{e}} = 1\ 836.152\ 673\ 4(15)$, which has a fractional precision of 8×10^{-10} and agrees on this level with recent proton-to-electron mass ratio values extracted from laser spectroscopy of simple molecular ions and precision Penning trap experiments.

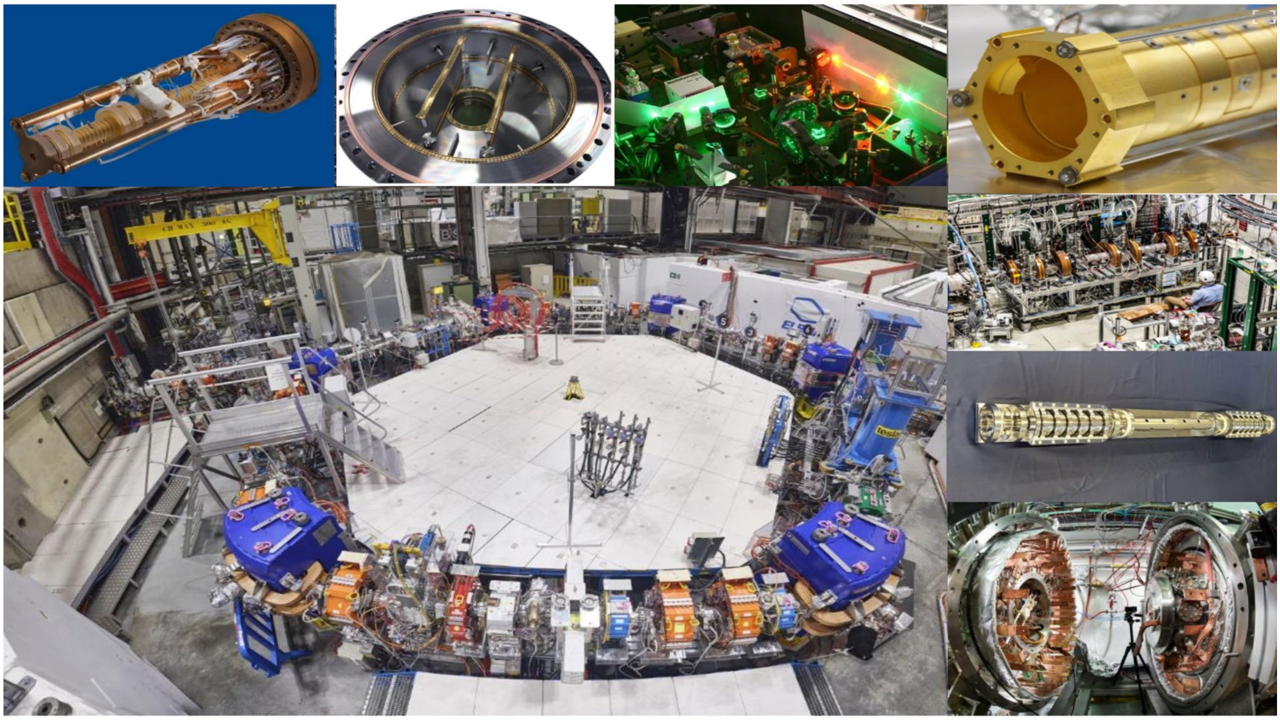

Figure 1. *Image of the installed ELENA ring. Insets clockwise: BASE multi-Penning-trap stack, ASACUSA microwave cavity and laser setup, ALPHA multi-ring electrodes, GBAR positron accumulator, PUMA MR-TOF separator, and AEgIS superconducting magnets.*

The ALPHA collaboration is performing precision measurements on the fundamental properties of $\bar{H}$ using an atom trap. After a development period that required the invention of several innovative plasma manipulation techniques, the collaboration reported in 2010 the first successful demonstration of $\bar{H}$-trapping. Based on this experimental success and by steadily improving their apparatus, ALPHA has meanwhile studied the charge neutrality of $\bar{H}$ with a record precision at the level of 7×10^{-10}, and demonstrated in a path-finder experiment a first low-resolution test of the free-fall weak equivalence principle. Most importantly, ALPHA has demonstrated the interaction of $\bar{H}$ with laser light in 2017. Based on this achievement they have measured the 1S/2S transition in $\bar{H}$ with a fractional resolution of two parts per trillion [3] and recently demonstrated laser cooling of antihydrogen. The BASE collaboration uses advanced Penning trap systems to compare the fundamental properties of protons and antiprotons. Their trap stack incorporates a purpose-built reservoir trap, in which they have demonstrated antiproton trapping for longer than a year, making the experiment almost independent of accelerator cycles. In fact, most of their precision studies are carried out while the facility is in shutdown mode. Using single particle nuclear magnetic resonance methods, single spin quantum transition spectroscopy, and a newly developed two-particle/three-trap technique, they have measured the antiproton magnetic moment with a fractional accuracy of 1.5 p.p.b. [2], which improved the previous best measurement by more than a factor of 3,000. Comparing cyclotron frequencies of antiprotons and negatively charged hydrogen ions H^-, they have recently compared the proton-to-antiproton charge-to-mass ratios with a fractional accuracy of 16 parts in a trillion. This measurement also enabled a first differential test of the clock weak equivalence principle in which a fractional accuracy of 0.03 was achieved, similar to the precision goals of experiments that test the free-fall weak equivalence principle studying the ballistics of antihydrogen in the gravitational field of Earth.

Thus, since the last report on the AD facility in this journal [15], our knowledge of antihydrogen and antiproton properties has tremendously improved. As shown in Figure 4, antiprotons' fundamental properties have been improved by up to six orders of magnitude. Antihydrogen spectral properties had never been measured until 2016 and are now known with a fractional precision, in the case of the 1S-2S transition, of 2 parts per

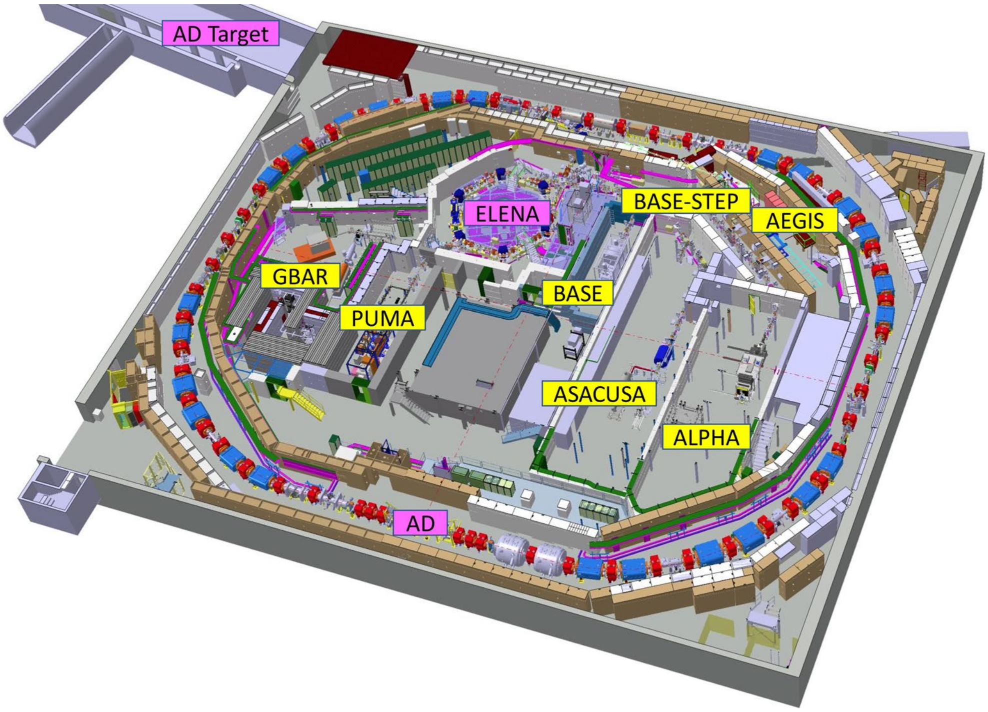

Figure 2. *Overview on the AD/ELENA facility. The AD, with a circumference of 183 m, constrains the area within which ELENA and the experimental areas are located.*

trillion. To push further these experiments and to generate progress at even higher momentum, CERN has developed the new synchrotron ELENA, which allows for much more economic use of the available antiprotons, enables future experiments that rely on improved beam-emittance, and effectively provides about a factor of four times more experiment time per collaboration.

Synchrotrons for Low-Energy Antiprotons

Rings for controlled deceleration and cooling of antiprotons and providing high-quality low-energy antiproton beams for physics have a long tradition at CERN [16]. The first such facility was the Low Energy Antiproton Ring (LEAR), conceived as an additional use of the antiproton accumulation complex built and maintained for the operation of the Super Proton Synchrotron (SPS) as a proton–antiproton collider, which mainly delivered ultra-slow extracted beams with very long spills. From the completion of the SPS collider program in 1992, the complex antiproton accumulation facility, consisting of a target area and (since 1987) of two rings, was operated and maintained only for LEAR. Thus, in order to save resources, it had been decided to discontinue the low energy antiproton program based on LEAR after the 1996 run.

The AD has been proposed as a simplified facility requiring the operation of only one synchrotron dealing with antiprotons and providing only bunched beams to the experiments running traps. To this end, the inner ring of the antiproton complex has been removed and the Antiproton Accumulator (AC) transformed from a fixed energy machine into a cycled one and renamed AD. The main modifications necessary to convert the AC ring into AD were: (1) cycled operation, (2) installation of an electron cooler requiring to modify the lattice, (3) upgrades of the vacuum system, (4) modification of the stochastic cooling system (only the lowest frequency band kept) to allow cooling at lower energy, and (5) the installation of extraction lines toward an experimental area located inside the ring. During an AD cycle lasting about two minutes, the beam is cooled at four different energies: at injection and at a second high-energy plateau with stochastic cooling and at low energy using electron cooling. The AD antiproton extraction energy of 5.3 MeV is a compromise: this energy is low enough to allow experiments to trap some antiprotons and use them for fundamental physics measurements,

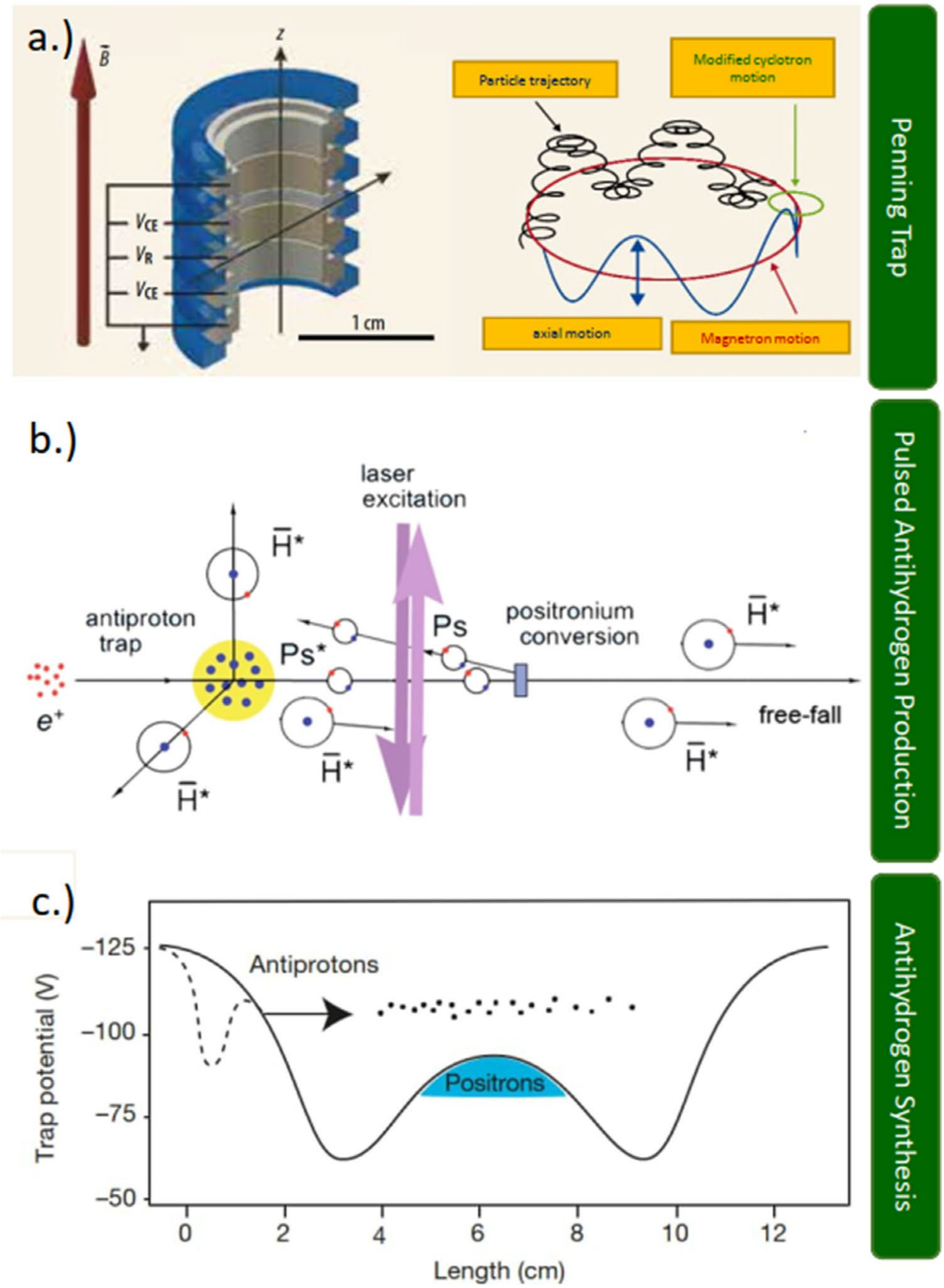

Figure 3. *Basic methods applied within the antimatter experiments. (a) A Penning trap (figure from Ref. [1]) consists of a strong magnetic field superimposed to electrostatic potentials; such a static superposition provides stable trapping of charged particles. The Penning trap is a crucial device within the AD program, for both experiments that measure the fundamental properties of antiprotons and experiments that synthesize antihydrogen based on antiproton and positron plasmas. (b) Schematics of a scheme for pulsed production of antihydrogen (figure from Ref. [13]). Positronium atoms in Rydberg states are interacting with a cold cloud of antiprotons held in a Penning trap. Charge exchange forms cold antihydrogen atoms. (c) Nested trap (figure from Ref. [3]) for the formation of cold antihydrogen. Cold high-density positrons, indicated in blue, are stored in the trap center; antiprotons are injected into the positrons. Antihydrogen is formed by a three-body recombination process.*

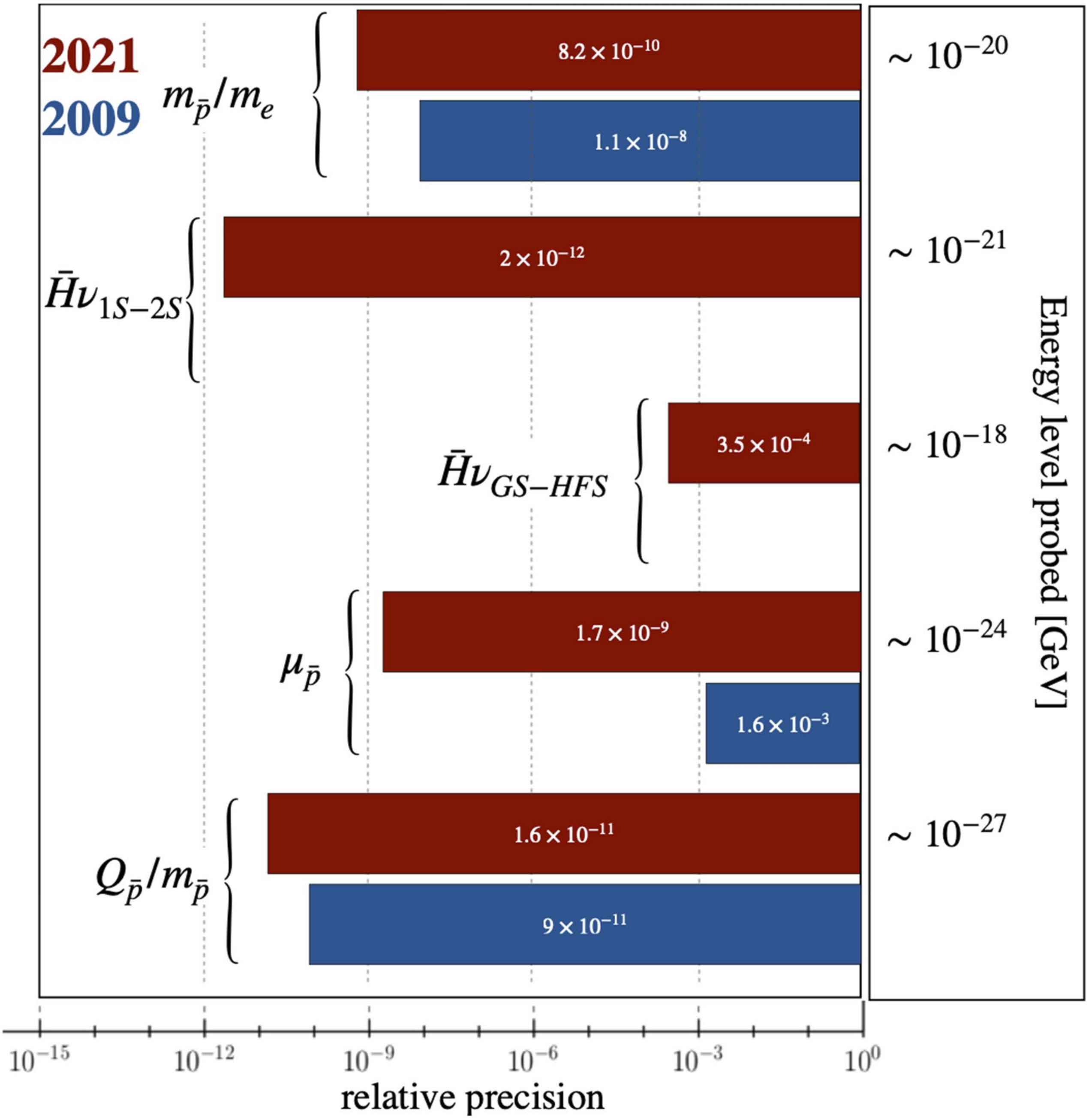

Figure 4. *2009 to 2022 status comparisons of measurements of matter and antimatter fundamental properties at the AD facility. The absolute precision reached on the frequency measurements is translated into an energy in the right insert as an indication of the energy level probed by the experiments.*

and is still high enough for reliable deceleration in the AD with the given circumference and magnetic system. However, during the AD era, the experiments had still to slow down the antiprotons by a large factor to the keV range to allow for trapping. This was typically done by foils, resulting in a trapping efficiency of less than 1% or by a Radio-Frequency Quadrupole (RFQ) decelerator leading as well to significant losses.

In order to allow experiments to increase their trapping efficiency by at least one order of magnitude, ELENA [17], a short 30.4 m circumference synchrotron, has been added to the facility to decelerate the antiprotons in a controlled way down to 100 keV. This energy can be reached with the new machine thanks to the reduced size and carefully optimized design. Magnets have been optimized to ensure sufficient field quality at low fields and the vacuum system is fully bakeable and coated with Non Evaporable Getters (NEG) surfaces. Particularly challenging have been the design and construction of beam instrumentation capable of measuring low-intensity, low-velocity beams, as well as the design and realization of a low-energy electron cooler. The ELENA deceleration cycle has an intermediate 650 keV plateau in addition to the 5.3 MeV injection and 100 keV ejection plateaus. The electron cooler is used on the intermediate plateau for reducing beam emittances and sizes to avoid losses during deceleration, and at the extraction energy to generate dense bunches for the experiments, which will allow them to increase the trapping efficiency by one to two orders of magnitude. The available intensity per shot is shared between four bunches, which can be sent to up to four different experiments in parallel. The initial motivation for this scheme was a limitation due to the so-called direct space charge effects: the electromagnetic field (Coulomb repulsion) created by the circulating bunches generates a nonlinear defocusing force, which would degrade the beam properties with only one bunch despite the low intensity due to the low energy and high brightness of the short bunches needed by the experiments. Sending up to four bunches to different destinations allows for almost continuous beam availability for the experiments, such that this scheme is considered an important improvement with respect to the AD era, when all available antiprotons were sent to only one experiment during typical eight-hour-long shifts. The antiproton bunches are extracted and distributed to different experiments by fast electric deflectors and electrostatic lines. This is a cost-effective solution at low energies, allowing a design with many quadrupoles keeping beam sizes small and less sensitive to perturbations, such as residual magnetic fields, which may be an issue at these low energies. ELENA has been installed inside the AD ring such that the experimental areas created with the AD could be maintained with minor modifications: the magnetic transfer lines from the AD have been replaced by electric ones delivering the antiprotons along the same trajectory. Two additional experimental areas were added inside the AD ring, together with ELENA. The ELENA ring was designed, constructed, and installed from 2012 on. The commissioning of the ELENA ring was completed in 2018 with the successful deceleration and delivery of 100 keV beams to the GBAR experiment. This was followed by the installation of the new transfer lines toward all other experiments, followed by their commissioning until the beginning of 2021. The first successful 100 keV antiproton run in 2021 marks the beginning of a new era for low-energy antiproton physics at CERN.

Outlook and Future Perspectives: Improved Precision Spectroscopy, Antimatter Transport, and Tests of the Weak Equivalence Principle

As future perspectives in the ELENA era, the CPT testing experiments will continuously improve their technologies to enhance the resolution of their experiments. The ASACUSA antiprotonic helium effort will immediately profit from the improved beam quality provided by ELENA and ALPHA will drastically enhance their resolution based on the much improved production rate made available in the ELENA era. The single particle experiment BASE will work on the implementation of the transportable antiproton trap BASE-STEP. The BASE experiments are currently limited by magnetic field fluctuations imposed by the AD/ELENA accelerators operating in the background. A relocation of the experiment to a less noisy, dedicated laboratory space will provide the potential to considerably improve the frequency resolution in those Penning trap–related experiments. The physics ideas of the newly approved PUMA collaboration rely as well on the transport of antiprotons. This collaboration plans to accumulate billions of antiprotons in a transportable Penning trap, to move the device to CERN's Isotope Mass Separator On-Line facility, and have the antiprotons annihilate on the surface of rare isotopes made available at this facility. This will allow PUMA to study inner tails of neutron skins, which have never been investigated before. In addition, the experiments that study the weak equivalence principle by investigating the ballistic properties of antihydrogen in the gravitational field of Earth will become operational.

Toward these goals, the AEgIS collaboration has already made substantial progress by demonstrating the first pulsed production of antihydrogen via a charge exchange mechanism [5] and prior to this performed a proof of concept of its Moire deflectometer technique with a beam of antiprotons [9].

The ALPHA collaboration has constructed the new experiment ALPHA-G, in which the production of antihydrogen has already been demonstrated. The GBAR collaboration is aiming at investigating the same physics, although using complementary methods. Their concept is based on a proposal that relies on the production of the charged antihydrogen ion $\bar{H}^+$. This particle can be sympathetically cooled to ≈ mK-temperatures, by coupling it to laser-cooled $^9\mathrm{Be}^+$ ions, drastically reducing the phase space volume of initial conditions of the planned ballistic experiment. Quasi momentum-less stripping of one of the positrons after sympathetic cooling combined with time-of-flight measurements, heralds free-fall weak equivalence principle tests with sub per-mille resolution.

In summary, the combination of new inventions by the AD collaborations together with the much improved antiproton source ELENA provide bright perspectives for the future of antiproton physics at CERN.

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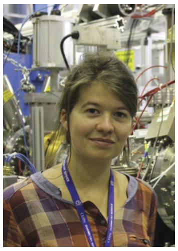

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