Prospective Nationale IN2P3 2020-2030 - GT01 - Physique des Particules

Precision Tests of Fundamental Interactions: Probing General Relativity with Antimatter

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Fabricating antihydrogen under controlled conditions in the lab offers the opportunity of studying fundamental symmetries underlying to the observable universe. The AD facility at CERN (the so-called "Antimatter Factory") is the sole installation worldwide providing low-energy antiproton beams to users. There are currently six experiments taking beam at the AD for studying physics involving antimatter: AEgIS, ALPHA, ASACUSA, ATRAP, BASE and GBAR. Figure 1 shows the layout of the AD facility at CERN, including all the above experiments and the new low-energy antiproton ring (ELENA) that provides 100-keV bunches of antiprotons [1]. Three of the AD experiments (AEgIS, ALPHA, and GBAR) are devoted to the study of the gravitational interaction of antimatter.

The cornerstone of the theory of general relativity is the weak-equivalence principle, which posits that the effect of gravity is independent of the nature and composition of a body in free fall. While many experiments have verified the WEP with matter, it has never been tested with antimatter. Certain aspects of grand unification theory predict differing interactions for matter and antimatter, which would result in a different value for the constants g and g-bar, perhaps offering insight into the mystery of dark matter and dark energy. IN2P3 is involved in two of the three experiments testing the free fall of antihydrogen: AEgIS [2] and GBAR [3]. Both experiments create antihydrogen using a charge-exchange reaction of low-energy antiprotons with positronium (a bound positron-electron pair), formed from collisions of positrons with a porous silica target: $\bar{p} + Ps^{*} \rightarrow \bar{H}^{*} + e^{-}$ (1), where $\bar{p}$ is the antiproton, *Ps** is positronium (* for an excited state), $\bar{H}$ is antihydrogen and e^{-} an electron.

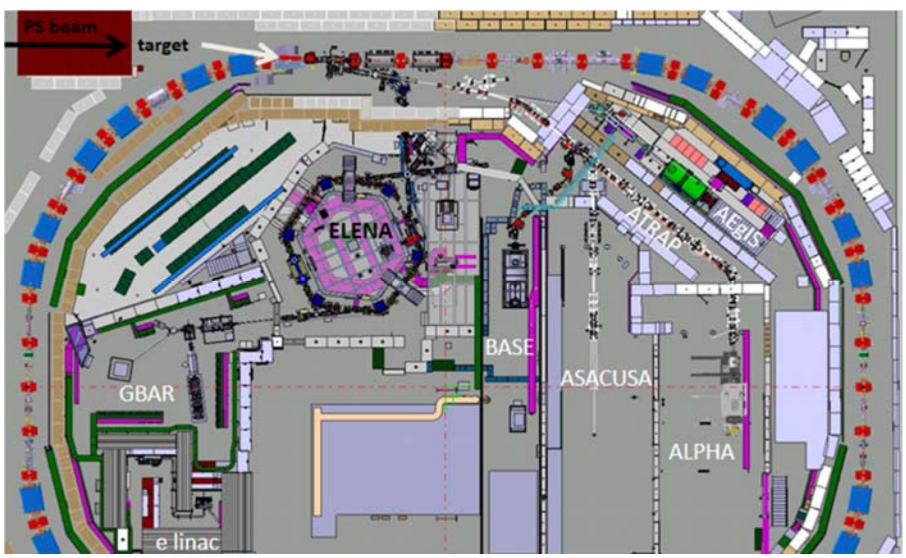

Figure 1: Overhead schematic of the "Antimatter Factory" at CERN. The 26-GeV SPS proton beam (top left) creates 3.5-GeV antiprotons that are directed into the 182-m circumference AD ring, where they are decelerated and cooled to 5 MeV over a period of 100 s. The AD then transfers the 5-MeV antiprotons to ELENA where they are futher decelerated (and cooled) to an energy of 100 keV.

Despite using the same antihydrogen recipe, the approaches of AEgIS and GBAR differ significantly. AEgIS launches a beam of antihydrogen atoms horizontally and measuring the gravity-induced vertical displacement by means of a position-sensitive detection device based on gratings and a high-spatial resolution detector for which first results have been achieved [4].

Compared to the ALPHA and ATRAP experiments, which are hampered by the difficulty of confining neutral antihydrogen after its formation, the distinguishing feature of GBAR is the use of the antihydrogen ion. GBAR will be the first experiment to fabricate an anti-ion, using a second charge-exchange reaction: $\overline{H} + Ps^{*} \rightarrow \overline{H}^{+} + e^{-}$, in which the antihydrogen produced in the first reaction interacts with another Ps to create an antihydrogen ion ($\overline{H}^{+}$), composed of one antiproton and two positrons. While this second reaction requires more ingredients, the advantage of the anti-ion is that it can be sympathetically cooled by Coulomb interaction with a laser-cooled beryllium-ion cloud. This allows reaching initial velocities of less than 1 m/s, which allows a precision measurement of g-bar.

Both AEgIS and GBAR rely on Ps laser excitation to increase the antihydrogen production cross-sections. AEgIS has already achieved results on Ps Rydberg states [5] while GBAR is still installing the laser systems to do this.

Goals of GBAR and prospects

The goals of GBAR as outlined in the proposal [3] are: to produce anti-hydrogen ions, cool them to μK temperature, photo-detach the anti-ions to leave a cold, neutral anti-atom and perform a free fall measurement on g with a 1% precision.

When fully installed, the GBAR apparatus (see Fig. 2) will consist of five main components:

1. A positron beam produced with a 9-MeV electron linear accelerator (NCBJ), a target and beam line followed by traps for e^{+} accumulation (IRFU).
2. GBAR will decelerate the 100-keV ELENA antiproton bunch electrostatically and use a pulsed-drift tube scheme (photograph in Fig. 2, right, IN2P3) to transform it to energies ranging from 1 - 10 keV [6]. The antiprotons are then accumulated in a trap, now being installed (Seoul University).
3. A reaction chamber to create antihydrogen (IRFU). Positrons are converted into positronium, which is excited with a laser (LKB). The unused antiprotons may be recycled back into the antiproton trap. A special setup is inserted to study the Lamb shift (ETH).
4. A vacuum chamber receives the anti-ion beam and hosts two Paul traps into which laser beams are focused to cool the anti-ion and perform the photo-detachment (Mainz/LKB).
5. A micromegas tracker detector (IRFU) and a scintillator-bar TOF array (SNU) detect the annihilation of the anti-atom and measure the time of its free fall.

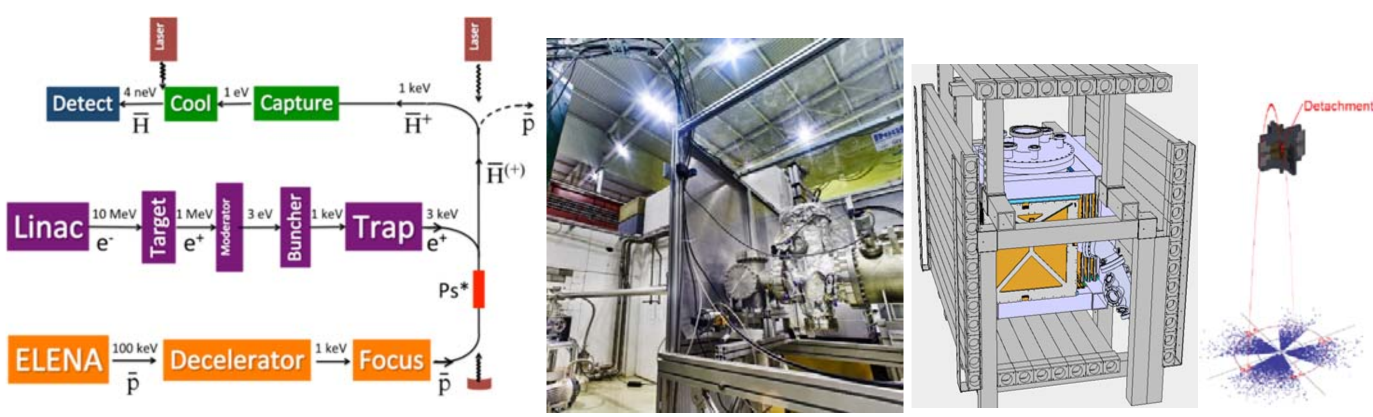

Figure 2: (left) Schematic diagram of the GBAR experiment, (middle-left) the antiproton decelerator, connected to ELENA, (middle-right) the tof array and micromegas-clad free-fall chamber, (right) schematic of free-fall measurement.

Most of the items in points 1 to 3 are installed and are being tested. The vacuum chamber of point 4 with its Paul traps and associated lasers are being made and tested at Mainz and Paris with a goal of installation in 2020. GBAR have obtained a flux of 5×10^7 slow positrons per second, while the goal in the proposal is 3×10^8. While there are no antiprotons, we use a proton gun that is operational and can also produce H^- ions. In addition to installation and tests, we also have a measurement program during LS2. As the laser to excite positronium is ready, we expect to measure the production cross sections under various conditions. Some of the hydrogen should be in the 2S state. This will allow measuring the Lamb shift of hydrogen in preparation for the same measurement with antihydrogen. Such a measurement would bring new constraints on CPT invariance and a first determination of the antiproton charge radius at a level of 10% [7].

When antiproton beams resume in 2021, we will apply the above methods to produce the antimatter counterparts, measure the Lamb shift with antihydrogen, capture and cool H^+ ions, and proceed with the free-fall experiment. This programme is already ambitious, but follows the scheme described in our proposal. A second stage of the proposal is to use an exotic scheme of quantum-reflected antiatoms [8]. Such scheme would allow obtaining an improvement of a factor 1000 on the precision on gbar with the same statistics. This is still planned for the period before LS3, depending on the outcome of the above program and the development of the apparatus.

In addition to the Lamb shift and antiproton radius, other ideas for experiments using the anti-ions have been proposed to the collaboration. The Paul traps may be built using the atom chip technology, as proposed by R. Folman from Ben Gurion University, underway in Mainz. This technology may then be applied to capture and trap the ultracold neutral antihydrogen atom and perform very precise spectroscopy. Another idea is to make anti H_2^+ ions, as proposed by E. Myers [9] for more precise tests of CPT than can be obtained from antiprotons and antihydrogen. These pursuits would require important modifications that are not all compatible with the free-fall experiment. They will thus be considered once the gravity experiment has been fulfilled.

The AEgIS Physics program and prospects

The AEgIS experiment [2] is based on the pulsed production of a beam of antihydrogen atoms, launched horizontally, and measuring the gravity-induced vertical displacement of ground-state antihydrogen atoms by means of a position sensitive detection device based on gratings and a high-spatial resolution detector, as shown on figure 3. Pulsed formation of antihydrogen is based on the same charge exchange process: $Ps^* + \bar{p} \rightarrow \bar{H}^* + e^-$. With such a pulsed-beam and grating based approach, the minimal acceleration a_{min} which can be resolved is given as a function of the detected number of atoms N_{det}, the signal visibility V, grating open fraction η, grating periodicity d, and the time τ=L/<v> with L being the grating separation and <v> the mean source velocity:

$$a_{min} = \frac{d}{2\pi V \eta \tau^2 \sqrt{N_{det}}}$$

A crucial figure of merit for the measurement is N_{det}, the number of atoms reaching the detector; the divergence of the formed beam is determined by the temperature (and space charge) of the antiprotons, and the efficiency of the beam formation mechanism. Furthermore, for identical divergence, reaching higher sensitivity greatly benefits from lower velocities. The challenges to be addressed in order to achieve a measurement of gravity with antihydrogen atoms are defined by these variables.

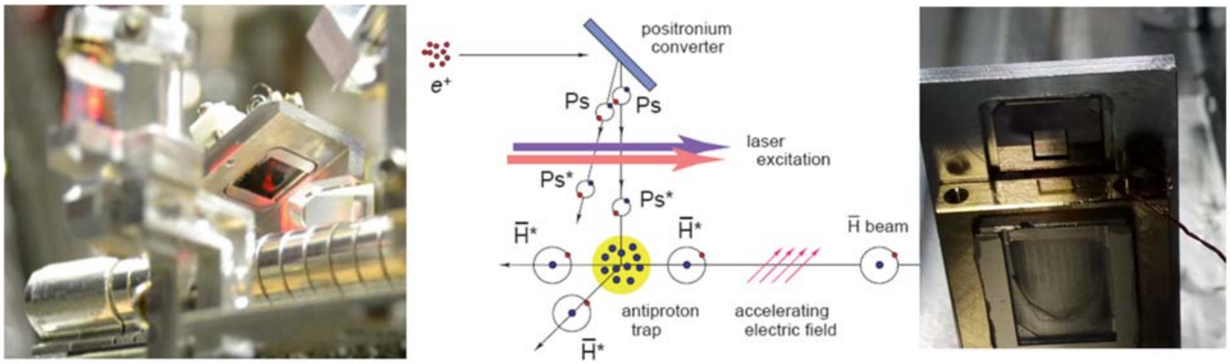

Figure 3: (middle) principle of the AEgIS Hbar formation; (left) zone of production of the Hbar showing the nanoporous Si target for oPs* production and the pbar Penning trap; (right) prototype of Talbot-Lau & moiré deflectometers for the free fall measurement.

In the last four years, AEgIS has worked towards validating the steps required for the pulsed formation of Rydberg antihydrogen atoms, achieving this goal at the end of 2018 [10]. We have reviewed the remaining challenges in reaching the goals of the proposal and have identified an expanded range of unique physics topics that the pulsed formation processes can provide as well as improving the prospects for a gravity measurement with antihydrogen. After having established pulsed formation of antihydrogen atoms in a Rydberg state, several challenges remain to follow the roadmap laid out in the proposal: number of antihydrogen atoms formed; formation of an antihydrogen beam; temperature of the formed antihydrogen atoms; Rydberg state vs. ground state antihydrogen; detecting gravity-induced deflections.

The process underlying the AEgIS physics program is pulsed production of antiatoms, whether it is positronium or antihydrogen atoms. In the case of positronium, the formed atoms have been subsequently laser-excited into long-lived states amenable to investigation [5]. In the case of antihydrogen, the formed Rydberg atoms can be electrically (Stark acceleration [11]) or optically (de-excitation into the ground state [12]) manipulated. The road map proposes an ambitious but, we believe, realistic path that develop expertise in a variety of related systems, where each advance benefits other systems, all of them building towards the goal of the AEgIS proposal.

In the immediate future, modifications to the AEgIS apparatus should allow achieving an enhanced production rate of $\bar{H}$ *. Together with prototype matter gratings and a detector under development, this could allow carrying out first tests of inertial sensing with Rydberg antihydrogen, albeit at a sensitivity several times larger than *g*. To proceed further, additional improvements will be required. AEgIS intends to focus on these in the near future (development of techniques to de-excite Rydberg atoms, laser-cooling of Ps, laser-cooling of C^-, improved pulsed $\bar{H}$ formation mechanisms), with each successful step gradually improving the sensitivity to that required for the goals of the proposal.

The goals for 2021/2022 are two-fold: an increase in the $\bar{H}$ source intensity and pulsed formation of the antihydrogen beam. Several possible paths lead to this goal, some of which allow access to pulsed formation of other antiprotonic atoms, and open the possibility of spectroscopic studies (via lasers in the case of Rydberg transitions, or via detection of the fluorescence x-rays for the deeply bound states) and even of probing the nuclear halo region at the end of the cascade. Such studies, while generally building on the existing capabilities and equipment, would benefit from additional detectors (e.g. for fluorescence detection) or require laser wavelengths not currently obtainable with the AEgIS laser systems. However, as the techniques overlap to a large extent, and as the optimal technique for formation of a cold beam of antiatoms amenable to gravity studies is dependent on a number of advances, we will incorporate sufficient flexibility in the apparatus to benefit from advances in any of the several pulsed formation techniques that need to be kept open as options.

In the following years, as either de-excitation of Rydberg atoms [12] or formation of colder antihydrogen/antiprotonic atoms [13] becomes feasible, and building on the experience with the initial grating / precision detector system, the sensitivity of the pulsed horizontal beam approach will be improved via finer gratings, possibly including optical gratings. The improvement in precision that can be reached has been simulated for specific assumptions on anti-atom formation rates and temperatures, leading to optimal grating sizes and required beam times (leading to the sensitivities detailed above). Further physics topics to be investigated in this period covers the areas of nuclear physics, atomic physics of antiprotonic species and inertial sensing. These developments are speculative, as they require a number of technological steps in order for them to become feasible.

Conclusion

AEgIS and GBAR (along with ALPHA-g, which has no IN2P3 involvement) aim at the first test of the Equivalence Principle from General Relativity with antimatter. The tantalizing potential for any difference in free fall with antimatter has far-reaching consequences for physics, from question of CPT violation to dark matter and quantum gravity, unifying the forces of nature. The two experiments are complementary and both have established strong links with atomic-physics groups in INP (LKB in the case of GBAR and LAC in the case of AEgIS). Although relatively small-scale experiments, they are quite complicated, coupling superconducting particle-storage devices to a large-scale accelerator facility, with low-energy manipulation and laser spectroscopy. The experiments are long term in terms of development and data taking. In addition to the main goals, a rich palette of physics opportunities is also provided.

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Annex

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New groups, their physics interests and their contributions (subject to successful funding requests) are listed below:

- <u>Czech technical university (Institute of Experimental and Applied Physics):</u> in addition to $\bar{H}$ simulations, ex-panded activity to also work on a spatially and temporally resolving anti-atom detector based on a hybrid MCP/silicon pixel detector assembly: positronium, antiprotonic atomic fluorescence spectroscopy, inertial sens- ing with anti-atoms
- <u>Warsaw:</u> fluorescence detectors, photon detector: protonium and physics at the annihilation threshold
- <u>Krakow:</u> Ps decay detector: positronium
- <u>PSI:</u> fabrication of material gratings: inertial sensing with anti-atoms
- <u>Raman Institute, Bangalore:</u> ion and atom trapping and manipulations, cooling