Report on the session “Antiproton Decelerator (AD)” at the New Opportunities on the Physics Landscape at CERN.

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The Case for the Antiproton Decelerator

1 . Physics motivation

The established physics is successfully described by the Standard Model (SM) and General Relativity (GR). However, many predictions of this theoretical framework currently remain experimentally unverified in the antimatter regime providing general impetus for tests involving antimatter. Concrete motivations arise in a number of theoretical approaches extending the SM and GR to include a consistent unified description of three cornerstones of physics: Lorentz symmetry, quantum mechanics, and gravity. The Standard-Model Extension(SME) governs a large set of the emerging effects relevant for low-energy antimatter experiments (for a recent review see[1]).

Access to low energy antiprotons ($\bar{p}$) offers excellent and unique opportunities to study the properties of fundamental forces and of symmetries in nature. Experiments with p can substantially contribute to our knowledge of atomic, nuclear and particle physics, in a complementary way to that to be acquired at the highest energy accelerators such as LHC. In particular, searches for new interactions, i.e. SME, can be carried out by studying discrete symmetries such as CPT, and furthermore, known interactions can be precisely tested and fundamental constants can be extracted from accurate measurements on free $\bar{p}$ and on bound two-and three-body systems such as antihydrogen ($\bar{H} = \bar{p}e^+$), the antiprotonic helium ion ($He^{++}\,\bar{p})^+$ and the antiprotonic atomcule ($He^{++}\,\bar{p}\,e^-$).

The prospect of performing spectroscopic investigations of antihydrogen, $\bar{H}$, opens the possibility for clean Planck-reach CPT tests[2]. Since CPT invariance is essentially a consequence of Lorentz symmetry and quantum mechanics, $\bar{H}$ spectroscopy probes these two important foundations of physics at interesting sensitivity levels [3]. Second, $\bar{H}$ is particularly well suited to determine the gravitational interaction of antimatter [4], which has never been adequately measured before. Since cold $\bar{H}$ production is currently only practical at the AD, this facility is uniquely positioned for essential experimental research at the interface of the aforementioned three cornerstones of physics.

The trapping of a single $\bar{p}$ in a Penning trap, the formation and precise studies of antiprotonic helium ions and atoms[5] and recently the production of $\bar{H}$ [6] have been among the pioneering experiments, which demonstrated the power of low energy $\bar{p}$ physics. They have led already to precise values for $\bar{p}$ parameters, accurate tests of bound two-and three-body Quantum Electrodynamics (QED), tests of the CPT theorem and a better understanding of atom formation from their constituents. They also contribute significantly already at this early stage to the NIST adjustment of fundamental constants[7].

The experimental program towards laser and microwave spectroscopy of $\bar{H}$ is progressing remarkably well, if compared to exotic atom spectroscopy in other systems. Future experiments promise more precise tests of the Standard Theory and have a robust potential to discover New Physics, in areas which can not be accessed with similar accuracy by other means. The central issue in precision physics is the control over systematic effects. That requires besides care and the necessary time to develop novel instruments and methods also adequate statistics in order to measure systematic effects with the appropriate care and accuracy. Precision experiments with low energy $\bar{p}$'s share therefore the need for intense particle sources and the need for time to develop novel instrumentation with all other experiments, which aim for high precision in exotic fundamental systems. There is no lack of ideas. The over-subscription of the AD program is the best indicator for the demand.

The experimental programs - carried out in the past mostly at the former LEAR facility and at present at the AD facility at CERN -will not only benefit from intense future sources of low energy $\bar{p}$'s. They are urgently needed for speedy progress. The highest possible p fluxes should not only be aimed for in the long run at new facilities such as the planned FLAIR facility at GSI[8]. In order to maximize the potential of delicate precision experiments to enhance our understanding of the basic forces in nature and to influence theoretical model building, the ELENA facility [9] is urgently needed. Examples of key $\bar{p}$ experiments have been discussed at this workshop and compared with other experiments in the field. Among the central issues is their potential to obtain important information on basic symmetries such as CPT. The $\bar{H}$ gravity experiments will be the only ones for the foreseeable future to gain crucial insights into antiparticle gravitation. Further a potential exists to learn about nuclear neutron distributions in $\bar{p}$ annihilation experiments. Other data needed for a number of experiments and upcoming facilities can be additionally gathered at a facility for $\bar{p}$'s at CERN with the highest possible $\bar{p}$ flux. Therefore ELENA is the way to go to maintain and boost a well motivated and challenging physics program with high visibility in science and in public.

2. Future of existing experiments

At present, four experiments take data at the CERN AD. The three experiments which are the heaviest users of beam time are alphabetically ALPHA, ASACUSA and ATRAP. The ACE experiment addresses the issue of $\bar{p}$ in cancer therapy.

The initial goal of ALPHA is to trap H atoms in a neutral magnetic trap so that they can be studied in detail. The long term goal is the spectroscopic comparison of H and $\bar{H}$. At present, ALPHA demonstrated the formation $\bar{H}$ in a neutral trap[10] and will concentrate in the next two years on trapping $\bar{H}$. In the next steps, the apparatus will have to be modified and expanded to perform a progression of increasingly precise microwave and laser spectroscopic measurements on $\bar{H}$.

ASACUSA's precision spectroscopy of antiprotonic helium atoms tests CPT invariance (*p* vs $\bar{p}$ mass comparison) and contributes to the CODATA fundamental physical constants [7,11]. In addition, ASACUSA has started to develop alternative methods to produce $\bar{H}$ atoms in a "cusp trap"[12] or in a superconducting Paul trap[13]. With these, the $\bar{H}$ ground-state hyperfine splitting will be measured. These precision experiments as well as other nuclear and atomic physics experiments which make use of ASACUSA's unique ultra low energy facility will benefit from ELENA's high-quality beam.

ATRAP continues to make good progress toward producing cold $\bar{H}$ in a state that can be trapped [14]. Though the production of $\bar{H}$ within the fields of a Penning-Ioffe trap has been demonstrated, no trapped atoms have yet been detected, presumably because the atoms formed are yet too energetic to be trapped. The latest substantial step towards atom trapping is in obtaining what seems to be 1.2 K plasmas of electrons and positrons from which it should be possible to obtain much colder $\bar{H}$ atoms than has previously been possible. A new Ioffe trap, under construction, promises to allow much more detection sensitivity for trapped $\bar{H}$ atoms. A solid-state Lyman alpha source is starting to produce some of the laser light that we will need to cool H atoms and to perform sensitive laser spectroscopy.

The ACE experiment [15] has not been represented at this workshop, yet the importance of studies that may contribute to cancer therapy taking into account the higher efficiency of radiation with $\bar{p}$ at a CERN facility cannot be stressed enough.

Much has been accomplished but much remains before the goals for which the AD was built are realized – the precise comparison of the properties of $\bar{H}$ and H atoms. Since for most experiments, the learning curve depends crucially on the number of delivered $\bar{p}$'s, they would all applaud an upgrade of the AD.

3. New experiments

The main goal of the proposed and recently approved AEGIS experiment [16] is the first ever measurement of the gravitational interaction of $\bar{H}$ to 1%. This requires developing new techniques to form a cold beam of $\bar{H}$, which will also allow in-flight spectroscopy of $\bar{H}$. The R&D is part of the experiment; a number of techniques requiring most or all of the final apparatus will be validated: formation of positronium in E ^{x} B-fields from a nano-structured target, laser excitation of positronium in E ^{x} B-fields, formation of Rydberg $\bar{H}$ and acceleration of Rydberg $\bar{H}$. Parallel R&D is being carried out with the goal of improving the efficiency of the experiment(laser-cooling of negative Os ions to obtain colder $\bar{p}$'s, simulations of field-manipulating Rydberg positronium). Investment costs will be most significant during the years of construction of the apparatus (2010-2012).

The physics program extends well beyond the foreseen extension of the AD to 2016, and would greatly benefit from the greater availability of $\bar{p}$'s that ELENA would allow.

In addition, new ideas have been presented at this workshop.

• "A measurement of the acceleration of $\bar{H}$ atoms in the gravity field of the Earth using $\bar{H}^+$ ions".

The aim of the experiment using $\bar{H}^+$-ions [17] is to measure the acceleration of ultra slow neutral $\bar{H}$ atoms in the Earth gravitational field. The production involves the charge exchange process $\bar{p} + P_s \rightarrow \bar{H} + e^-$, followed by $\bar{H} + P_s \rightarrow \bar{H}^+ + e^-$.

The excess positron is then photodetached in order to recover a neutral and slow $\bar{H}$ (μK temperatures). The R&D is in progress on high density positronium formation and e^+ production, as well as positronium excitation and e+ trapping (2011). Antiproton trapping, based on ASACUSA experience, should be improved. Ion sympathetic cooling and photo-detachment R&D should be launched as soon

As possible with $\bar{p}$'s. Matter counterpart of some of the above reactions could be measured by 2012. An electron linac should be installed at the AD aroub this time to produce an intense slow e^+ flux. The free fall measurement could be completed in 2014.

• "Measurement of the spin-dependence of the $p\bar{p}$ interactions at the AD-ring".

The idea is to use an internal polarized *H* storage-cell gas-target in the AD-ring to determine for the first time the two total, spin-dependent, $p\bar{p}$ cross sections, σ_1 and σ_2 at $\bar{p}$ beam energies in the range from 50 to 450 MeV. A Technical Proposal will be submitted at the beginning of April to the SPS committee at CERN.

• "Double-strangeness production with $\bar{p}$'s at the AD-ring".

The physics goal of the experiment is the study of double-strangeness production with stopped $\bar{p}$'s and search for $\bar{K}$-mediated deeply bound nuclear clusters that contain two $\bar{K}$'s, like K^-K^-pnn. The possibility of their existence is a hot topic in the further understanding of kaon nucleon/nuclei reactions and for the study of chiral restoration in a nuclear medium[18]. A 4π detector is needed consisting of a magnetic spectrometer for the identification of charged particles and a calorimeter for the detection of neutral decay products. The central detector is a time projection chamber with GEM readout, which is currently being developed within a Joint Research Activity in the FP7 project "Hadron Physics 2". A fully operational prototype will be built within this project till middle of 2011. A collaboration will be formed, capable of building the detector and target system, within the next 6 months. In parallel funding has to be secured. It is planned to build and test the setup within the next three years, so that it could be installed at the AD, earliest in the 2012/2013 shutdown. An operation for 3 years with one month per year is foreseen for the initial program at the AD. More detailed studies are planned at FLAIR after successful studies at the AD.

• "Antiprotonic atom X-ray studies at AD from selected elements with low Z."

The study of light antiprotonic atoms gives access to various phenomena both of strong interaction and cascade effects originating from the interplay of the electron shells with the $\bar{p}$ during the de-excitation cascade occurring after capture[19].

4 . Overview of low-energy $\bar{p}$ facilities

The AD facility at CERN is unique – at present, no low-energy $\bar{p}$ facilities other than the AD exist. The next facility to possibly come on line is FLAIR, at the earliest in 2016 and more realistically in2 018 (finances have not yet been approved and political support is still required). FLAIR will provide a 1000-fold increase of trapped $\bar{p}$'s over the AD and a 10-fold increase of trapped $\bar{p}$'s over the AD+ELENA, as well as significantly more floor space for experiments. Current progress in the experiments at the AD towards trapping of $\bar{H}$ is limited by the availability of $\bar{p}$'s, and reaching the physics goals of the current round of experiments would be greatly facilitated by the ELENA low-energy decelerator.

The formation of $\bar{H}$ typically requires a large number of $\bar{p}$'s at high densities which cannot be achieved at the present $\bar{H}$ experiments with a single AD bunch. Stacking techniques are used to increase the number of trapped $\bar{p}$'s. The efficiency of the experiments would be hugely improved and the productivity and the availability of the unique user facility AD at CERN with its great scientific potential would be greatly enhanced if a further deceleration and cooling storage ring would be installed between the AD and the experiments. Such a ring could be the suggested ELENA ring[9]. It is envisaged that ELENA will increase the phase space density at 100 keV by one to two orders of magnitude, depending whether the experiments are already using the RFQD or not, respectively. This would raise the efficiency of the $\bar{p}$/ $\bar{H}$ program at CERN by a very large factor. The construction of a rather small machine for this purpose is feasible. The main challenges for such a project of deceleration to very low energies, such as ultra low vacuum and effective electron cooling, can be managed. The proposed ELENA ring can be located inside the AD hall without large modifications. All installation work for ELENA can be done without significant influence on the AD operation for physics, but for commissioning some extra time would have to be scheduled.

The experience gained at existing low-energy storage rings such as AD (CERN), ASTRID (Aarhus), TSR (Heidelberg), and CRYRING (Stockholm) can be exploited in the design and construction of ELENA.

5. Summary

CERN not only leads the world in ”high energy” physics. It has long also distinguished itself by pursuing fundamental particle physics at lower energy scales when the laboratory possesses the unique capability to do so. CERN introduced the world's lowest energy $\bar{p}$'s at 5 MeV. Experimenters at LEAR and then the AD introduced particle traps to lower the energy by up to an additional ten orders of magnitude in energy, making it possible to compare *q/m* for the $\bar{p}$ and p at the 9 parts in 10^{10} level. Now, $\bar{H}$ is being formed by two different methods at the AD. The expectation is that $\bar{H}$ spectroscopy will provide comparisons of $\bar{H}$ and H at much higher precision. Formation of beams of $\bar{H}$ in the ground state is an alternative approach to trapping and also allows to study the gravitational properties of $\bar{H}$. The newly proposed experiments would further reduce the availability of $\bar{p}$'s. An upgraded AD, able to deliver many more $\bar{p}$'s at lower energies to experiments, would speed the progress.

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