Low Energy Antiproton Experiments – A Review

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Abstract. Low energy antiprotons offer excellent opportunities to study properties of fundamental forces and symmetries in nature. Experiments with them can contribute substantially to deepen our fundamental knowledge in atomic, nuclear and particle physics. Searches for new interactions can be carried out by studying discrete symmetries. Known interactions can be tested precisely and fundamental constants can be extracted from accurate measurements on free antiprotons ($\bar{p}$’s) and bound two- and three-body systems such as antihydrogen ($\bar{H} = \bar{p}e^-$), the antiprotonic helium ion ($\text{He}^{++}\bar{p}$) and the antiprotonic atomcule ($\text{He}^{++}\bar{p}e^-$). The trapping of a single $\bar{p}$ in a Penning trap, the formation and precise studies of antiprotonic helium ions and atoms and recently the production of $\bar{H}$ have been among the pioneering experiments. They have already led 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. Future experiments promise more precise tests of the standard theory and have a robust potential to discover new physics. Precision experiments with low energy $\bar{p}$’s share 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. The experimental programs - carried out in the past mostly at the former LEAR facility and at present at the AD facility at CERN - would benefit from intense future sources of low energy $\bar{p}$’s. The highest possible $\bar{p}$ fluxes should be aimed for at new facilities such as the planned FLAIR facility at GSI in order to maximize the potential of delicate precision experiments to influence model building. Examples of key $\bar{p}$ experiments are discussed here 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 and to gain insights into antiparticle gravitation as well as the possibilities to learn about nuclear neutron distributions.

INTRODUCTION

The availability of beams of low energy antiprotons ($\bar{p}$) has led to a number of precision experiments on the properties of free $\bar{p}$’s, of simple two- and three-body bound systems and to studies concerning the interactions of $\bar{p}$’s with matter. Central to the motivation for the precision experiments is the goal to test fundamental forces and symmetries in physics, in particular the CPT invariance \cite{1,2}.

To date we know four fundamental interactions: (i) Electromagnetism, (ii) Weak Interactions, (iii) Strong Interactions, and (iv) Gravitation. These forces are considered fundamental, because all observed dynamical processes in physics can be traced back to one or a combination of them. Together with fundamental symmetries they form a framework on which all physical descriptions ultimately rest. The Electromagnetic, the Weak and many aspects of the Strong Interactions can be described to astounding precision in one single coherent picture, the Standard Model (SM). Gravity is not included in the SM. It is a major goal in modern physics to find a unified quantum field
theory which includes all the four known fundamental forces in physics. A satisfactory quantum description of gravity remains yet to be found.

In modern physics - and in particular in the SM - symmetries play an important and central role. Whereas global symmetries relate to conservation laws, local symmetries yield forces \[ \mathfrak{g} \]. It is rather unsatisfactory that within the SM the physical origin of the observed breaking of discrete symmetries in weak interactions, e.g. of parity (P), of time reversal (T) and of combined charge conjugation and parity (CP), remains unrevealed, although the experimental findings can be well described. Further, there are observed conservation laws which have no status in physics, as there is no symmetry known from which they could be derived, e.g. conservation of baryon and lepton numbers.

Among the intriguing questions in modern physics are the hierarchy of the fundamental fermion masses and the number of fundamental particle generations. Further, the electro-weak SM has a rather large number of some 27 free parameters. All of them need to be extracted from experiments.

The spectrum of speculative models beyond the standard theory, which try to expand the SM, includes such which involve left-right symmetry, fundamental fermion compositeness, new particles, leptoquarks, supersymmetry, supergravity and many more. Interesting candidates for an all encompassing quantum field theory are string or membrane (M) theories which in their low energy limit include supersymmetry.

Searches for effects predicted in speculative models can be carried out in accelerator experiments at the highest at presently possible energies, where, e.g., the direct production of new particles can be looked for. Complementary, at low energies one can look for small deviations from accurate predictions within the SM in high precision experiments. Low energy antiproton experiments are important examples of such precision experiments. In this article we describe precision low energy antiproton experiments and compare them in physics potential and experimental techniques with related low energy precision experiments in other systems.

**ANTIPROTON SOURCES**

Today there exists only one facility for low energy antiproton research, the Antiproton Decelerator (AD) at CERN. It succeeded the former LEAR facility and delivers about $10^5 \overline{p}$/s and has only pulsed extraction ($3 \times 10^7 \overline{p}$ in a 100 ns long pulse every 85 seconds). The AD output energy is 5 MeV. This relatively high kinetic energy is a major disadvantage of the AD. For the experimental programme energies below 100 keV would be much better suited. To achieve this, typically degrader foils are used and one obtains about 2500 $\overline{p}$/s per AD pulse. The AD serves three experimental areas occupied by the ASACUSA, the ATHENA and the ATRAP collaborations. The AD serves a physics program including the spectroscopy of antiprotonic atoms and $\overline{H}$ and investigations of the $\overline{p}$ interaction with matter.

Recently an ultra slow monoenergetic $\overline{p}$ beam could be extracted with relatively high efficiency. A radiofrequency quadrupole (RFQ) decelerator was employed to achieve $1.2 \times 10^6$ particles per AD pulse could be obtained. When loaded into a multiring trap (MRT) and with electron cooling beams of 10-500eV energy could be made [4]. This
FIGURE 1. At present only the Antiproton Decelerator (AD) facility at CERN provides low energy $\overline{p}$'s for precision experiments. A possible upgrade with the ELENA storage ring could increase the $\overline{p}$ flux significantly. In the long term future the FLAIR facility at GSI could provide low energy $\overline{p}$'s for a variety of experiments at somewhat higher rates.

The new development presents a major step forward and could open new research fields with ultra slow $\overline{p}$'s, in particular precision tests of fundamental interactions.

At CERN a new Extra Low ENergy Antiproton ring (ELENA) has been proposed, which would be installed behind the AD. One expects 300 ns wide bunches in the energy range 5.3 MeV to 0.1 MeV. Slow extraction appears possible. The space charge limit of the device is about $1.7 \times 10^7$ particles; the longitudinal and transverse temperatures are expected in the 100 eV range.

In connection with the future upgrade plans of GSI, Germany, into a Facility Antiproton and Ion Research (FAIR) also a Facility for Low-energy Antiproton and Ion Research (FLAIR) is foreseen. This promises cooled $\overline{p}$ beams of $1 \times 10^6 \overline{p}$/s at 300 keV, and $5 \times 10^5 \overline{p}$/s at 20 keV. Emittances of $1 \pi$ mm mrad and a momentum spread of $< 10^{-3}$ are possible which is a significant improvement in brilliance over the present...

FIGURE 2. The multiring trap at the CERN AD facility which achieved 10-500 eV $\overline{p}$ beams [4].
FIGURE 3. A possible upgrade of the CERN AD facility with the LENA ring (left) could increase the $\bar{p}$ flux significantly. In the long term future the FLAIR facility (right) at FAIR(GSI) could provide low energy $\bar{p}$'s for a variety of experiments at somewhat higher rates.

AD facility.

PROPERTIES OF ELEMENTARY PARTICLES – STORED AND TRAPPED LEPTONS AND BARYONS

The properties of elementary particles offer opportunities to test standard theory, and to search for new physics. Particularly the comparisons of particle and antiparticle properties have often been reported as tests of the CPT theorem, which predicts that except for the sign of their electric charge (and charge related quantities) particles and antiparticles should be identical (see Fig. 4).

Trapping and storing of charged particles in combined magnetic and electric fields has been very successfully applied for obtaining properties of the respective species and for

FIGURE 4. Tests of the CPT theorem comparing particle and antiparticle properties. Reported is the limit of the fractional differences achieved. Also shown are expectations from $\bar{H}$ experiments.
determining most accurate values of fundamental constants. Most accurate results were obtained from single trapped and cooled charged particles. The comparison of proton (\(p\)) and \(\bar{p}\) has already reached an impressive level of precision (see Fig. 4).

**Leptons**

The magnetic anomaly of fermions \(a = \frac{1}{2} \cdot (g - 2)\) describes the deviation of their magnetic g-factor from the value 2 predicted in the Dirac theory. It could be determined for single electrons and positrons in Penning traps by Dehmelt and his coworkers to 10 ppb \([9]\) by measuring the cyclotron frequency and its difference to the spin precession frequency (g-2 measurement). The good agreement for the magnetic anomaly for electrons and positrons is considered the best CPT test for leptons \([2]\). Accurate calculations involving almost exclusively the "pure" QED of electron, positron and photon fields allow the most precise determination of the fine structure constant \(\alpha\) \([10, 11]\) by comparing experiment and theory for the electron magnetic anomaly in which \(\alpha\) appears as an expansion coefficient (see Fig. 5). One order of magnitude improvement appears possible \([12]\) with a new experimental approach (also involving single cooled trapped particles) which aims for reducing the effect of cavity QED, the major systematic contribution to the previous experiment \([13]\).

Muons have been stored in series of measurements at CERN and BNL in magnetic storage rings with weak electrostatic focusing, which is conceptually equivalent to Penning traps. The latest experimental results \([14]\) yield values for positive and negative muons which agree at the 0.7 ppm level in agreement with CPT. The muon is by a factor \((\frac{m_e}{m_M})^2\) more sensitive to heavy particles compared to the electron. The muon g-2 measurements are sensitive to new physics involving heavy particles at 40,000 times lower experimental precision. Whether the present experimental results are in agreement with standard theory remains an open question, as not sufficiently accurate values for

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**FIGURE 5.** Measurements of the electron magnetic anomaly using single electrons confined and cooled in a Penning trap yield the best values for the fine structure constant \(\alpha\).
corrections due to known strong interaction effects exist yet.

**Protons and Antiprotons**

After moderation of a $\bar{p}$ beam from LEAR at CERN, $\bar{p}$'s could be trapped in a cylindrical Penning trap for the first time in 1986 [15]. Effective moderation of MeV $\bar{p}$'s and their capture were very important, which has led to detailed studies of the range differences when $p$’s and $\bar{p}$’s are slowed down in matter, known as the Barkas effect[16]. Further electron cooling is essential and could be demonstrated already in the early experiments [17].

In a series of measurements in which the cyclotron frequencies were measured the accuracy of the charge to mass ratio for $\bar{p}$’s could be improved (see Fig. 6) and compared to the proton value. The best results were achieved when a single H$^-$ ion and a single $\bar{p}$ where measured alternatively in the same trap [19]. At present these experiments are interpreted as a CPT test for $p$ and $\bar{p}$ at the level of $9 \times 10^{-11}$. A new experiment has been proposed to measure the magnetic g-factor of the $\bar{p}$ using single particle trapping. Similar to measurements on single electrons and positrons the cyclotron and spin precession frequencies shall be determined. One expects for the comparison of $p$ and $\bar{p}$ g-factors an improvement by a factor of $10^6$ [6].

![FIGURE 6. Left: Cylindrical Penning trap for $\bar{p}$'s [15]. Right: The charge to mass ratio of protons and $\bar{p}$'s could be measured from the cyclotron frequency in a Penig trap. The fractional uncertainty was constantly improved. The best value was reached, when a single $\bar{p}$ was stored and compared to H$^-$ ions [18,19].](image)

**HYDROGEN-LIKE ATOMS**

Next to single particles, H-like atoms (see Table I) are the simplest systems in atomic physics. The electromagnetic part of their binding can be calculated to very high precision in the framework of QED [11,20]. This allows to study the influence of other known interactions in the Standard Model such as strong and weak forces. Also new yet unknown interactions beyond the Standard Model can be searched for when the precise
The ground state hyperfine structure splitting $\Delta v_{HFS}$ and the 1S-2S level separation $\Delta v_{1S-2S}$ of H and some exotic H-like systems offer narrow transitions for studying the interactions in Coulomb bound two-body systems. In the exotic systems the natural linewidths $\delta v_{HFS}$ and $\delta v_{1S-2S}$ have a fundamental lower limit given by the finite lifetime of the systems, because of annihilation, as in the case of positronium and antiprotonic helium, or because of weak muon or pion decays. The very high quality factors (transition frequency divided by the natural linewidth $\Delta v / \delta v$) in H and other systems with hadronic nuclei can unfortunately not be fully utilized to test the theory, because of the insufficiently known charge distribution and dynamics of the charge carrying constituents within the hadrons. The purely leptonic systems are not affected by this complication.

|                  | Positronium | Muonium | Hydrogen / Antihydrogen | Muonic Helium4 | Pionium | Muonic Hydrogen | Pionic Hydrogen | Antiprotonic Helium4 ion | Protonium |
|------------------|-------------|---------|--------------------------|----------------|---------|----------------|------------------------|--------------------------|-----------|
| $\Delta v_{1S-2S}$ [THz] | 1233.6      | 2455.6  | 2466.1                   | 2468.5         | 2458.6  | 4.59×10^5     | 5.8810^5              | 9×10^7                   | 2.25×10^7 |
| $\delta v_{1S-2S}$ [MHz]   | 1.28†       | .145    | 1.3×10^-6                | .145           | 12.2    | .176           | 3.510^7                | 10^6                    | 2.5×10^5  |
| $\Delta v_{HFS}$          | 9.5×10^8    | 1.7×10^{10} | 1.9×10^{15}             | 1.7×10^{10}    | 2.0×10^8| 2.6×10^{12}  | 1.710^4                | 10^3                    | 10^2      |
| $\delta v_{HFS}$          | 203.4       | 4.463   | 1.420                    | 4.466          | --      | 4.42×10^7     | --                     | --                      | 2.1×10^-6 |
| $\Delta v_{HFS}$          | 1.7×10^2    | 3.1×10^4 | 3.2×10^{24}             | 3.1×10^4       | --      | 3.1×10^8     | --                     | --                      | 8×10^-12  |
standard theory calculations are confronted with precision experiments. In the past 50 years the chain of three natural isotopes has been significantly expanded with artificially created “exotic” atoms, which often allow to study aspects of fundamental interactions more precisely than the natural atoms.

The H-like atoms fall in three groups: (i) purely leptonic systems such as postitronium ($e^+e^-$) and muonium ($\mu^+e^-$), (ii) systems containing leptons and hadrons, such as the natural H ($pe^-$), deuterium ($de^-$) and tritium ($te^-$), but also antihydrogen ($\bar{p}e^+$), pionium ($\pi^+e^-$), muonic hydrogen ($pm^-$), the muonic helium atom ($\mu^+e^-$) and antiprotonic helium atom ($He^{++}\bar{p}e^-$) and (iii) purely hadronic systems such as pionic hydrogen ($p\pi^-$), the antiprotonic helium ion ($He^{++}\bar{p})$ and protonium ($p\bar{p}$). Although in principle three-body systems, the atoms of muonic helium and antiprotonic helium may be regarded as hydrogen-like, as one may consider the ($He^{++}p^-\bar{p}$) and ($He^{++}p$) bound systems as pseudo-nuclei orbited by the lighter ($e^-$). It should be mentioned that the antiprotonic helium atom with the $\bar{p}$ in an excited state shows both properties of an atom and of a molecule and therefore has been named an “atomcule” [48].

Positronium

The positronium atom (PS) as a particle-antiparticle bound system is its own antiatom. This causes that in the theoretical description virtual annihilations play an important role and cause significant level shifts. PS has been formed in gases, powders and at certain metal surfaces. The development of sources providing the atoms at thermal velocities in vacuum or in the vacuum of the intergranular regions in powders has taken several decades after the discovery of the atom [21]. This provided a base for later precision experiments. Electromagnetic transitions have been measured in PS with microwave spectroscopy such as the ground state hyperfine splitting and the fine structure transitions in the first excited state of the triplet system. All are in good agreement with standard theory. The $1^3S_1$ and $1^3S_1$ energy difference has been determined with Doppler-free laser spectroscopy to 2.5 ppb. This has been interpreted as the best test of the equality of electron and positron masses [22].

The annihilation of triplet positronium into three gammas has been reported to deviate from SM calculations over the last decade. Recent measurements[23] are in good agreement with theory [24] (see Figure 7). Apparently systematic errors had been underestimated in the past. Sensitive searches for rare positronium decays, e.g. decays into C-parity violating numbers of photons or into new particles such as axions, have not given any result which would be inconsistent with the SM. More sensitive searches are underway and motivated by a number of speculative models [24].

Muonium

Muonium (M) consists of an antiparticle ($\mu^+$) and a particle ($e^-$) [26] and is therefore to be considered in part as antimatter. This fact causes some principle differences in the interactions in the bound state compared to H. Well understood are the differences
FIGURE 7. The history of orthopositronium lifetime measurements (from [24]).

casted (i) by the the different muon and proton masses, which lead to different reduced mass effects, (ii) by the different anomalous magnetic moments reflecting the significantly different muon and proton g-factors due to the proton's internal structure, and (iii) by different signs in the weak interaction contributions to level energies, because the proton is a particle and the muon is an antiparticle.

In the early years muonium research concentrated on measurements that were possible with atoms created by stopping muons in a gas and studying them in this environment [25]. All high precision experiments in M up to date atom have involved the 1s ground state (see Fig.8), in which the atoms can be produced in sufficient quantities. M at thermal velocities in vacuum can be obtained by stopping $\mu^+$ close to the surface of a SiO$_2$ powder target, where the atoms are formed through $e^-$ capture and some of them diffuse through the target surface into the surrounding vacuum, or from hot metal surfaces. This process has an efficiency of a few percent. Only moderate numbers of atoms in the metastable 2s state can be produced with a beam foil technique. Because furthermore these atoms have keV energies due to a velocity resonance in their formation. Electromagnetic transitions in excited states, particularly the n=2 fine structure and Lamb shift splittings could be induced by microwave spectroscopy. However, the experimental accuracy is 1.5 %, which represents not a severe test of theory. The detailed work over 3 decades since the discovery of M in order to understand the atom formation resulted in improvements of the efficiency and quality of M sources. It was indispensable for the success of novel precision experiments [26].

For the M ground state hyperfine structure splitting the constant improvements in experimental techniques resulted in a factor of 10 gain in the accuracy every six years for a period of 20 years after the atom had been discovered. Today the experiments are limited by the available muon fluxes. This is the main reason why the accuracy improvement became slower. The latest measurements of the M hyperfine structure
FIGURE 8. The energy levels of H and $\overline{H}$ (right) and M (left) are identical and standard theory predicts exactly the same energy differences. Muonium energy levels differ mainly because of the differences in the proton and muon masses and magnetic moments. At a smaller scale a difference arises from proton internal hadronic structure. New and yet unknown interactions such as CPT or lepton number violation forces could cause additional small energy shifts, which could be revealed in precision experiments. (not to scale)

which yield important fundamental constants such as the muon magnetic moment or $\alpha$ were performed at LAMPF, the brightest quasi-pulsed muon source, which delivered $10^8 \mu^+/s$. The experiment reached 12 ppb accuracy [27] and was only limited by statistics.

The process of muonium to antimuonium-conversion (M-$\overline{M}$) violates additive lepton

FIGURE 9. The accuracy of M $n = 1$ state hyperfine structure measurements over four decades.
family number conservation. It would be an analogy in the lepton sector to the well known $K^0-\bar{K}^0$ and $B^0-\bar{B}^0$ oscillations in the quark sector. As the oscillations are hindered by gas collisions, the availability of $M$ in vacuum was essential for significant progress.

When thermal $M$ atoms in vacuum from a SiO$_2$ powder target, could be observed for their decays in an apparatus covering a large solid angle, three and a half orders of magnitude improvement were possible for the limit on the conversion probability which led to severe restrictions for several speculative models [28]. Again these results are limited by statistics, i.e. the available particle fluxes.

With the availability of thermal $M$ atoms in vacuum from either SiO$_2$ powder or hot metal surfaces, laser spectroscopy became possible. It took one decade from the pioneering Doppler-free 1S-2S two-photon transitions at KEK [29] to the precision experiment at RAL [30] where 4 ppb accuracy was achieved which led to the best test of the equality of muon end electron charges at 2 ppb. Some 15 years after the first laser experiment in $M$ a novel technique succeeded to obtain ultraslow polarized muons through resonant photo ionization of $M$ [31]. Very recently a first muon spin rotation signal with muons from such a source was reported. This development is very important for surface and thin film science.

Precise CPT tests from comparing particle and antiparticle properties (see Fig. 4) neglect in part the fact that symmetry violations ought to be connected with an interaction. Furthermore, the CPT theorem relates to many more intriguing features in physics than particle properties. Recently, generic extensions of the Standard Model, in which both Lorentz invariance and CPT invariance are not assumed, have attracted widespread attention in physics. In particular, new approaches try to quantify CPT violation through additional terms in the Lagrangian of a system [32]. For $M$ diurnal variations of the ratio $\nu_{12} - \nu_{34} / (\nu_{12} + \nu_{34})$ could be a sign of Lorentz and CPT violation (see Fig. 10). An upper limit can be set at $2 \cdot 10^{-23}$ GeV for the relevant parameter. In a specific model by Kostelecky and co-workers a dimensionless figure of merit for CPT tests is sought by normalizing this parameter to the particle mass. In this framework $\Delta \nu_{HFS}$ provides a significantly better test of CPT invariance than electron $g$-2 and the neutral Kaon oscillations [33].

![Breit Rabi diagram of the M ground state and absence of significant sidereal oscillation in the ratio of transition frequencies between Zeeman levels in a 1.7 T magnetic field](image)

**FIGURE 10.** Left: Breit Rabi diagram of the $M$ ground state. Right: The absence of a significant sidereal oscillation in the ratio of transition frequencies between Zeeman levels in a 1.7 T magnetic field confirms CPT invariance at the best level tested for muons.
Hydrogen

Atomic H has not only enormously contributed to the development of modern physics, in particular to quantum mechanics and QED. Spectroscopic techniques have been pushed forward in attempts to gain ever higher accuracy. Microwave techniques around the H maser and laser techniques and Doppler-free spectroscopic methods are among the examples.

In atomic H the ground state hyperfine structure splitting at 1.42 GHz is used in H masers. It’s high quality factor (ratio of transition frequency to natural linewidth) of $3.2 \times 10^{24}$ makes it interesting for a secondary frequency standard. The reproducibility of experimental setups, e.g. H masers, provides the major limitation here to a long term stability of order $10^{-14}$. The transition frequency itself has been measured (compared to the Cs frequency standard) to 0.006 ppb [34]. However, the accuracy of bound state QED calculations is limited to the ppm level due to the proton’s internal structure which is not well enough known for calculations of similar accuracy. The main uncertainty arises from the distribution of magnetism within the proton, i.e. its magnetic radius.

Doppler-free two-photon spectroscopy in a cryogenically cooled atomic beam of H yielded the 1S-2S energy interval with a relative uncertainty of $1.8 \times 10^{-14}$ [35]. The coldest H beam one can imagine at this time results from two-photon laser extraction from a H Bose condensate [36, 37]. Typical parameters for the H 1S-2S transition are: a saturation intensity of $I_s = 0.9 \text{W/cm}^2$; an excitation rate of $R_e = 4\pi \times 84 \times (I/W/s \times \text{cm}^2)^2/\Delta v_{\text{exp}}/\text{Hz}$, where I is the laser intensity and $\Delta v_{\text{exp}}$ is the actual observed linewidth of the transition; a 2S state photo-ionization rate $R_p = 9 \times I/W/s \times \text{cm}^2$; a Zeeman shift of $\delta v_Z = 93 \times B \text{kHz/T}$, with a magnetic field B; an ac-Stark shift of $\delta v_{\text{ac}} = 1.7 \times I \text{Hz/W cm}^2$. At 1 mK temperature the average velocity of the atoms is 4 m/s causing in a typical 600 \mu m diameter beam a time-of-flight broadening of $\Delta v_{\text{exp}} = \Delta v_{\text{TOF}} = 3\text{kHz}$. Assuming that a 1S-2S transition is observed with an MCP after field quenching of the 2S state a $10^{-6}$ overall detection efficiency (intrinsic efficiency $\times$ solid angle) must be taken into account. For $10^{11}$ atoms of 30 \mu K in a trap a relative uncertainty for the line center of $\delta v/v_{1s-2s} = 10^{-13}$ has been achieved in 1 s integration time [37]. (It should be noted that at saturation intensity the ionization rate is of order $1.7 \text{s}^{-1}$ and that the atoms can be used essentially only once, because after the transition the $m_F$ states get equally populated.) In the absence of systematic effects the uncertainty of the line center scales as

$$\delta v = \Delta v_{\text{exp}}/(\text{Signal}/\text{Noise}) = \Delta v_{\text{exp}}/\sqrt{N},$$

where $N$ represents the number of observed transitions which is in approximation proportional to the number of atoms in the laser field. The reachable precision depends strongly on the number of available atoms.

A limit on the time variation of $\alpha$ was extracted from two series of repeated measurements of the 1s-2s energy difference in H over a long time and $\frac{d\alpha}{dt} = \frac{d\alpha}{dt}(\ln \alpha) = (-0.9 \pm 2.9) \times 10^{-15} \text{y}^{-1}$ could be established [38]. We note, the two series have reduced $\chi^2$ values of 4.2 respectively 9, which may be viewed as a hint that present experiments suffer from not well understood systematic errors. Therefore, presently optical spectroscopy appears to be limited at the $10^{-13}$ level of relative accuracy.
FIGURE 11. Right: Measurements of the 1S-2S transition frequency in atomic H have been reported with continuously improving relative uncertainty down to the $10^{-14}$ level due to ever improving technology. Left: Two series of precision measurements of the 1s-1s energy difference in H over 4 years time allow to extract a limit on the time variation of the fine-structure constant $\alpha$ [38].

**Antihydrogen**

**Antihydrogen Formation**

$\bar{H}$ was produced first at CERN in 1995 [39]. The atoms were fast as the production mechanism required $e^+e^-$ pair creation when $\bar{\eta}$’s were passing near heavy nuclei. A small fraction of the $e^+$ form a bound state with the $\bar{\eta}$. The experiment was an important step forward showing that a few $\bar{H}$ could be produced. Unfortunately, the speed of the atoms does not allow any meaningful spectroscopy. Later a similar experiment was carried out at FERMI LAB [40].

The successful production of slow $\bar{H}$ was first reported by the ATHENA collaboration in 2002 [41] and shortly later also by the ATRAP collaboration [42]. Both experiments use combined Penning traps in which first $e^+$ and $\bar{\eta}$ are stored separately and cooled. The atoms form when both species are brought into contact by proper electric potential switching in the combined traps. The detection in ATHENA relies on diffusion of the neutral atoms out of the interaction volume and the registration of $\eta$’s which appear when the atoms annihilate on contact with matter walls of the container. In ATRAP the hydrogen atoms are re-ionized in an electric field and the $\bar{\eta}$’s are observed using a capture Penning trap.

Most of the atoms are in excited states ($n > 15$) which can be seen from the fact that their physical size is above $0.1 \mu m$ [43]. For spectroscopy the atoms need to be in states with low $n$, preferentially the ground state. The production of such states is a major goal of the community for the immediate future. The kinetic energy of the produced $\bar{H}$ atoms has been measured to be of order 200 meV corresponding to a velocity of $6 \times 10^4$ m/s. This is a factor of 400 above the value where neutral atom traps can hold them. Therefore cooling such atoms or identifying a production mechanism for colder $\bar{H}$ are a central topic.
For laser cooling of $\bar{\text{H}}$ a continuous laser at the H Lyman-$\alpha$ frequency for $\bar{\text{H}}$ cooling has recently been developed. One hopes to achieve the photo-recoil limit of 1.3 mK.

Recently a promising new method was demonstrated to obtain antihydrogen. It uses resonant charge exchange with excited positronium to obtain $\bar{\text{H}}$ atoms with essentially the same velocities as the $\bar{\text{p}}$’s in the trap which can be made rather low by cooling.

### CPT Tests with Antihydrogen

A main motivation to perform precision spectroscopy on $\bar{\text{H}}$ is to test CPT invariance. There are two electromagnetic transitions which offer a high quality factor (see Table 1) and therefore promise high experimental precision when $\bar{\text{H}}$ and $\text{H}$ are compared: the 1S-2S two-photon transition at frequency $\Delta \nu_{1S-2S}$ and the ground state hyperfine splitting $\Delta \nu_{\text{HFS}}$, which both have within the SM in addition to the leading order contributions from QED, nuclear structure, weak and strong interactions,

$$\Delta \nu_{1S-2S} = \frac{3}{4} \times R_\infty + \epsilon_{\text{QED}} + \epsilon_{\text{nucl}} + \epsilon_{\text{weak}} + \epsilon_{\text{strong}} + \epsilon_{\text{CPT}} \quad (2)$$

$$\Delta \nu_{\text{HFS}} = \text{const} \times \alpha^2 \times R_\infty + \epsilon^*_{\text{QED}} + \epsilon^*_{\text{nucl}} + \epsilon^*_{\text{weak}} + \epsilon^*_{\text{strong}} + \epsilon^*_{\text{CPT}}. \quad (3)$$

In eq. (2) and eq. (3) it is assumed that only CPT violating contributions exist from interactions beyond the SM. If one assumes that $\epsilon_{\text{CPT}}$ and $\epsilon^*_{\text{CPT}}$ are of the same order of magnitude, there relative contributions is larger by order $\alpha^{-2}$ for $\Delta \nu_{\text{HFS}}$. Further one can speculate that a new interaction may be of short range (contact interaction), which also favors measurements of $\Delta \nu_{\text{HFS}}$. Such an experiment has been recently proposed. It utilizes a cold $\bar{\text{H}}$ atom beam and has sextupole state selection magnets in a Rabi type atomic beam experiment. For both experiments eq. (1) governs the reachable

![Image](image_url)
precision, i.e. the atoms should be as cold as possible and one should use as many as possible atoms.

**Gravitational Force on \( \overline{H} \)**

One of the completely open questions in physics concerns the sign of gravitational interaction for antimatter. It can only be answered by experiment. A proposal [46] exists (see Fig. 13) in which the deflection of a horizontal cold beam is measured in the earth’s gravitational field. The experiment plans on a number of modern state of the art atomic physics techniques like sympathetic cooling of \( \overline{H}^+ \) ions by ,e.g. Be\(^+\) ions in an ion trap to achieve the neccessary low temperatures of some 20 \( \mu \)K . After pulsed laser photodissociation of the ion into \( \overline{H} \) and a \( e^+ \) the neutral atoms can then leave the trap. The atom’s ballistic path can be measured.

![Diagram](image)

**FIGURE 13.** The sign of the gravitational force on atomic \( \overline{H} \) needs to be determined by experiment, as there is no experimental evidence yet that antimatter and matter show identical behavior concerning gravity [46].

**ANTIPROTONIC HELIUM**

The potential of antiprotonic helium for precision measurements in the field of fundamental interaction research was realized shortly after it had been discovered that \( \overline{p} \)'s stopped in liquid or gaseous helium exhibit long lifetimes and do not rapidly annihilate with nucleons in the helium nucleus [48]. This can be explained, if one assumes that the \( \overline{p} \)'s are captured in metastable states of high principal quantumnumber \( n \) and high angular momentum \( l \), with \( l \approx n \) (see Fig. 14 [49]). The capture happens at typically at \( n \approx \sqrt{M^*/m_e} \approx 38 \), where \( M^* \) is the reduced mass of the \( (\overline{p}\text{He}) \) bound system.

With laser radiation the \( \overline{p} \)'s in these atoms can be transferred into states where Auger de-excitation can take place. In the resulting H-like system Stark mixing with s-states results in nuclear \( \overline{p} \) absorption and annihilation which is signaled by emitted pions. This way a number of transitions could be induced and measured with continuously increasing accuracy over the past decade. A precision of \( 6 \times 10^{-8} \) has been reached for the transition frequencies [50], which has been stimulating for improving three-body
In the formation process of antiprotonic helium the capture of the $\bar{p}$ into a state with quantum numbers $n \approx 38$ and maximal $l$ is very likely. Such states are rather stable against $\bar{p}$ annihilation [48].

QED calculations. It should be noted that with the high principal quantum numbers for the $\bar{p}$ the system shows also molecular type character [51].

Among the spectroscopic successes the laser-microwave double resonance measurements of hyperfine splittings of $\bar{p}$ transitions could be measured (see Fig. 15) [53]. There

![Graph showing energy levels and transitions in antiprotonic helium](image)

**FIGURE 14.** In the formation process of antiprotonic helium the capture of the $\bar{p}$ into a state with quantum numbers $n \approx 38$ and maximal $l$ is very likely. Such states are rather stable against $\bar{p}$ annihilation [48].

**FIGURE 15.** Example of a line splitting due to hyperfine structure in antiprotonic helium [53].
FIGURE 16. Accurate QED calculations have been performed for antiprotonic $\bar{p}^4\text{He}^+$ and $\bar{p}^3\text{He}^+$. The differences between the results from independent calculations are below the accuracy achieved in experiments. These differences may be regarded as an indication of the size of systematic uncertainties in the theoretical approaches chosen [55].

...is greement with QED theory [54] at the $6 \times 10^{-5}$ level which can be interpreted as a measurement of the antiprotonic bound state g-factor to this accuracy. In principle, hyperfinestructure measurements in antiprotonic helium offer the possibility to measure the magnetic moment of the $\bar{p}$.

**CPT tests with Antiprotonic Helium Ions**

The very good agreement of the QED calculations with the measurements of several transitions can be exploited to extract a limit on the equality of the charge to mass ratio for proton and $\bar{p}$. Combined with the results of cyclotron frequency measurements [19] in Penning traps one can conclude that masses and charges of proton and $\bar{p}$ are equal within $6 \times 10^{-8}$ in full agreement with expectations based on the CPT theorem [55]. The collaboration estimates that a test down to the 10 ppb level should be possible.

**ANTIPROTONIC (RADIOACTIVE) ATOMS**

It has been shown at the LEAR facility at CERN that antiprotonic x-rays from atoms in which a $\bar{p}$ has been captured can be utilized to obtain information on the neutron mean square radii of nuclei (see Fig. 17, 56). The accuracy of the experiments is limited at present by nuclear theory. Neutron distributions are expected to be the limiting factor in the theory of the upcoming round of precision experiments on atomic parity violation. In particular some radioactive nuclei of Francium and Radium isotopes are of interest. At a combined radioactive beam and antiproton facility one can expect experiments to determine the neutron radii with sufficient accuracy for, e.g., the needs...
of theory to describe improved atomic parity violation experiments including such in heavy radioactive atoms.

**STATUS OF SLOW ANTIPROTON PHYSICS (SPRING 2005) - CONCLUSIONS**

Low energy antiproton research has made already a number of important contributions to test fundamental symmetries and to verify precise calculations. With cyclotron frequency measurements of a single trapped $\bar{p}$ and with precision spectroscopy of antiprotonic helium ions stringent CPT tests could be performed on $\bar{p}$ parameters. With precise measurements of $\bar{p}$ in antiprotonic helium atomcules the bound state QED three-body systems could be challenged, which has led to significant advances already. With antiprotonic heavy atoms new input could be provided to obtain neutron radii of nuclei. The differences in proton/ antiproton interactions with matter could expand on similar work with other particle/ antiparticle systems.

$\bar{\Pi}$ atoms have been produced by two independent collaborations. Precision spectroscopy of these atoms will depend on the availability of atoms in the ground state, the successful cooling of the systems to below the 100 $\mu$eV range and their confinement in neutral particle traps. Work in this direction is in progress. A comparison with other exotic atom experimental programs shows that one must allow for sufficient time to de-
velop the necessary understanding of production mechanisms and one must allow time for improving the techniques. The experiments will benefit in their speed of progress and in their ultimate precision from future slow $\bar{p}$ sources of significantly improved particle fluxes and brightness as compared to today’s only operational facility.

The ongoing and planned experiments bear a robust discovery potential for new physics, in particular when searching for CPT violation. We can look forward to future precision $\bar{p}$ experiments continuing to deepen insights in fundamental interactions and symmetries, providing important data and parameters with standard theory and providing improved searches for new physics.

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