Antimatter Factory

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It is intended to plan a facility to produce antinuclei and antiatoms as much as heavy (Antimatter Factory).

Antinuclei up to mass number $A = 3$ have been created at CPS, AGS and U-70. Antialpha particles are not yet detected, even though present high energy accelerators/colliders, such as SPS, Tevatron, RICH and LHC, are able to produce, energetically and in principle, much hevier antinuclei, antinucleus production (with anti mass number A) shall be exponentially more difficult with increasing A. This is because hot-spot (fire ball) formed by high energy collisions could produced as many anti-baryons (anti quarks) as compared to baryons (quarks), but emitted hadrons from the surface (hadronization) layers of fire balls shall be dominantly mesons, barions and their antis, only tiny parts of anti barions can form $\overline{d}$, ${}^3\overline{H}$, ${}^3\overline{He}$.

To investigate seriously the difference, if any, among matter (nucles, atoms, ...) and antimatter, we may wish to have various antinuclei ($A \geq 4$) and antiatoms. High energy accelerators/colliders at presently running are not able to produce ${}^4\overline{He}$ and heavier antis. Then it may be better to try to cook heavy nuclei from accumulated antiprotons. In a way our synthesis looks similar to primordial nucleo synthesis just after the Big Bang and nuclear synthesis at central zones of main sequence stars.

However there exist several differences. We can not store antineutrons $\overline{n}$. We can not rely on weak and radiative processes, such as $\overline{p} + \overline{p} \to \overline{d} + e^- + \overline{\nu_e}$, (p, γ) reactions. Production ratio $\overline{d}/\overline{p}$ at high energies is small $\sim 10^{-3}$. Therefore, it seems we must first mass-produce $\overline{d}$ from $\overline{p}$. Such a production method has already been proposed at GSI, utilizing the reaction $\overline{p} + \overline{p} \to \overline{N} + \overline{\Delta} \to \overline{d} + \pi^-$ with the energetically asymmetric $\overline{p} - \overline{p}$ collider. After enough accumulation of $\overline{d}$, $\overline{p} + \overline{d}$ and $\overline{d} + \overline{d}$ shall produce ${}^3\overline{H}$, ${}^3\overline{He}$. $\overline{d} +^3 \overline{H}$ and $\overline{d} +^3 \overline{He}$ will produce ${}^4\overline{He}$. Repeated use of $(\overline{d}, \overline{p})$ and $(\overline{d}, \overline{n})$ we may cook heavire nuclei.

To realize these nuclear reactions we need storage rings (and colliding zone) of several 100 MeV/c and relevant bending magnets.

Such facility, consisting of set of asymmetric colliders (a few GeV/c and a few 100 MeV/c) and beam transports, beam cooling parts, if constructed, may be useful to measure cross sections of many nuclear reactions (including radiative capture process) relevant to nucleo synthesis after Big Bang and of astrophysical importance. Such measurement may also serve to the Fusion Projects for energy production.

Furthermore, μ^+ catalyzed fusion may be tried to produce very light antinuclei.

This facility may cost substantially. But there must be many (used part of) colliders and detectors, already shut down, in the world. Economical use of such parts is the way to cost down.

Eventually I wish to see the synthesis of nuclei (atoms) up to the heaviest. Very accurate test of properties of antinuclei (atoms) must uncover something new different from nuclei (atoms), beside the accurate check of CPT theorem, etc.

Testing the validity of the equivalence principle with antimatter: the AEGIS experiment

G. Testera[1] on behalf on the AEGIS collaboration

The validity of the Equivalence Principle for antimatter has never been directly experimentally demonstrated. The AEGIS [1] experiment at the CERN accelerator AD has been recently recommend for approval by the CERN scientific committee and it is aiming to perform a direct measurement of the Earth's acceleration g on antihydrogen.

Progresses in the formation of cold antihydrogen and positronium together with that in the field of acceleration and deceleration of Rydberg atoms by using Stark forces have opened the way toward this ambitious goal.

By merging these technologies and including some realistic upgrading, the AEGIS experiment will form a beam of cold antihydrogen and it will use a Moire' deflectometer coupled to a position sensitive detector to obtain the g value.

A description of the project will be given with emphasis on its experimental perspectives and challenges.

[1] AEGIS proposal, CERN-SPSC-2007-017, CERN-SPSC-P-334, Jun 2007

Production of cold antihydrogen for precision studies

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The proposed AEGIS experiment at the CERN antiproton decelerator will constitute the first-ever experimental test of the effect of gravity on antimatter. Its performance crucially depends on the temperature of the initial antihydrogen sample. Measurements by ATRAP and ATHENA have shown that antihydrogen produced with the nested-trap technique is much hotter than the temperature of the surrounding trap, a fact which is attributed to an unexpectedly high recombination rate which exceeds the cooling rate of antiprotons in a positron plasma. Therefore, novel schemes for antihydrogen recombination as well as for the pre-cooling of antiprotons are being considered and will be tested prior to the construction of the AEGIS apparatus. If demonstrated to be successful, such techniques will be applicable to a wide range of current and future precision antimatter experiments.

Baryogenesis and its implications to fundamental physics

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How the imbalance between matter and anti-matter emerged in the big bang universe was a great conundrum until 30 years ago. Around that time a consistent theory of particle interaction has been established as the standard gauge theory. Prior to this time and already in mid 70's there have been speculations that the standard model based on SU(3) x SU(2) x U(1) may be further unified into a larger gauge theory unifying all 3 interactions among quarks and leptons. It is in this atmosphere when lively discussions on speculative ideas of baryogenesis have been initiated. Since then, it has been a hot subject among theorists, and now many particle physicists regard the baryogenesis as one of the key issues to probe physics beyond the standard theory.

In this overview I shall review some general ideas and fundamental issues of baryogenesis. It is presented with some personal taste of historical perspective[1].

The emphasis of baryogenesis has shifted from the original GUT idea [2] towards a new one based on leptogenesis [3]. This is understandable in view of the experimental discovery of the neutrino oscillation. Some of the key elements of leptogenesis can be checked experimentally either by detection of neutrinoless double beta decay, or by some new idea. I shall thus touch on how this experimental vindication might become possible based on our new experimental method [4].

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Accelerating universe, WEP violation and antihydrogen atoms

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We start with showing how the discovery of the accelerating universe can be understood by a nonzero cosmological constant, which allows an interpretation in terms of a scalar field, a yet to be discovered partner of the spacetime metric field in the language of Einstein's general relativity. We also show how the scalar-tensor theory of gravitation, a well-studied theoretical alternative to general relativity, provides a solution to today's version of the cosmological constant problem. We emphasize that the theoretical analysis suggests the Weak Equivalence Principle (WEP) to be violated rather naturally. Further from the point of view of unifying particle physics and gravitation, a vector field may also be included in the list of Non-Geometric Gravitational Fields (NGGF). We then show two types of the detailed calculation on antihydrogen atoms to test WEP.

A new path to measure antimatter free fall

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We propose an experiment to measure the free fall acceleration of neutral antihydrogen atoms. The originality of this path is to first produce the $\bar{H}^+$ ion. This ion can be cooled down to μK temperatures (i.e. m/s velocities) according to Walz and Hänsch [1]. The excess positron can then be laser detached in order to recover the neutral $\bar{H}$ atom. This process can be set up to minimize momentum transfer in the vertical direction. The temperature achieved in cooling of the $\bar{H}^+$ ion gives the main systematic error. This ion is produced through the charge exchange process $\bar{p} + Ps \rightarrow \bar{H} + e^-$, followed by $\bar{H} + Ps \rightarrow \bar{H}^+ + e^-$. The matter counterpart of the first process has been measured [2] in agreement with calculations with cross sections of order 10^{-15} cm^{-2} [3]. The calculated cross section for the second process is 10^{-16} cm^{-2} [4]. Thus if 10^7 antiprotons interact with a density of 10^{12} cm^{-3} Ps atoms, 1 $\bar{H}^+$ ion is produced, together with 10^4 $\bar{H}$ atoms. Collecting 1000 events should provide a 2% measurement error on g.

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SPAN − Spectroscopy by Atomic Neutrinos

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We propose a new novel method to measure fundamental parameters associated with neutrinos[1]. It utilizes the neutrino pair emission from atomic levels.

One of the important questions left in the particle physics is related to the neutrino parameters. These involve their mass nature, Dirac or Majorana, absolute mass values, and their mixing parameters which appear in the weak interactions. As is well known, the recent oscillation experiments firmly established neutrinos' finite masses. However, these experiments can determine only mass-squared differences of three neutrino species. One naive view is to take two heavier neutrinos have masses suggested by the mass scales of the atmospheric and solar oscillation experiments, respectively, and the lightest one much smaller than the two;

$$m_3 \sim 50\ \text{meV}, \qquad m_2 \sim 10\ \text{meV}, \qquad m_1 \ll m_2. \tag{1}$$

How to measure such small masses and how to determine their mass nature? Experiments so far aiming to answer these questions tend to utilize nuclear processes, which usually involve much larger energy scale; for example the tritium beta decay end point energy is 18.6 keV.

We propose to employ neutrino pair emissions from atomic levels to determine neutrino absolute masses;atomic level spacings are much closer to expected neutrino mass scale. As will be discussed, other parameters can be measured simultaneously with the mass determination. The main difficulty in the method lies in the smallness of weak processes. Typically neutrino emission rate scales with $G_F^2 Q^5$, where G_F is the Fermi coupling constant and Q is the available energy in the process. The rate is usually very small and we need some enhancing mechanism to realize such experiments.

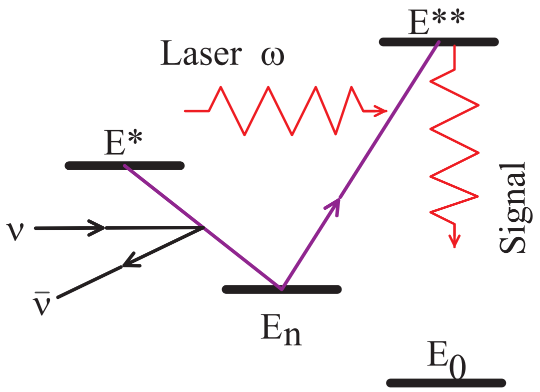

Figure 1: Laser irradiated neutrino pair emission level scheme.

We employ several methods for this purpose; one is a laser irradiated pair emission which use a resonance effect for enhancement. The relevant scheme is shown in fig.1. The other is to make use of collective nature of atoms. We discuss the prospect of Spectroscopy by Atomic Neutrinos[2].

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Precision measurements of the positronium decay rate and Energy level

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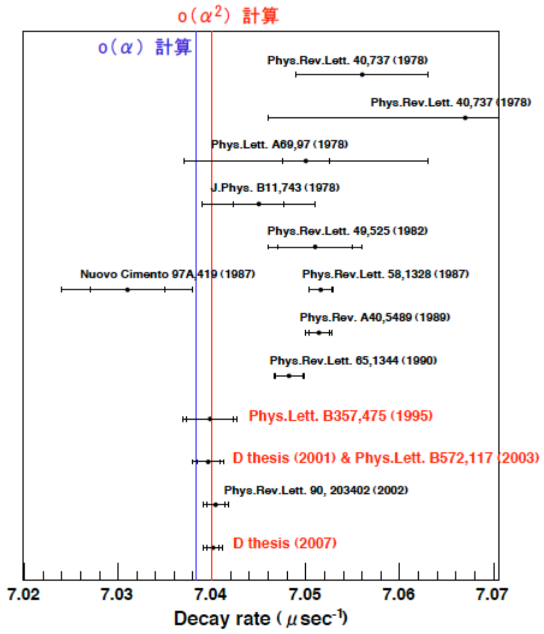
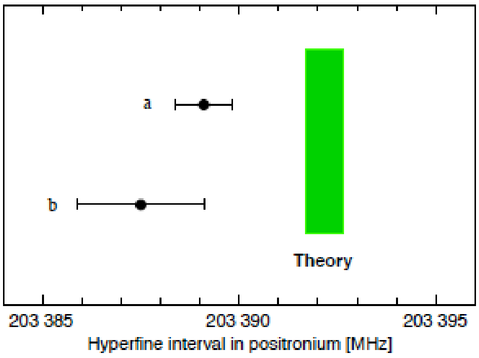
Positronium, the bound state of an electron and positron, is a pure quantum electro-dynamical (QED) system providing a highly sensitive field for study of the bound state QED. The higher order calculations of 2nd and 4th order have been performed recently on the orthopositronium(o-Ps Triples State 1^3S_1) decay rate and the energy splitting between o-Ps and parapositroniumu(p-Ps: singlet State 1^1S_0), respectively. The spin-spin interaction and an annihilation diagram (o-Ps -> gamma* -> o-Ps) contribute the energy splitting (HFS: Hyperfine Splitting), which is very sensitive a new physics beyond the Standard Model because of the quantum effects of the new physics to the annihilation diagram. The precision measurements of the decay rate and HFS give a good test of the bound state calculations and probe the new Physics. Large discrepancy (>1000ppm), called as "o-Ps lifetime puzzle", has been reported in the 1980s and 90s. We found that a thermalisation process of o-Ps is slower than our expectation and the unthermalized o-Ps makes large bias on the measurement of the o-Ps decay rate. We proposed the new method to determine the thermalization process and the effect of the collision between the o-Ps and the materials directly. We performed precision measurements with this method and obtained the consistent with the QED predictions as shown in the right figure.



New measurement with the fast scintillator, YAP, has been performed in 2007, and obtain the most precise result with an accuracy of 130 ppm. The world average of the resent four measurements is 7.0401 +- 0.0007 μs^{-1} (error 100ppm) , which is consistent with the 2nd order correction and differ by 2.6 σ from the 1st order prediction. This is the first result on the 2nd order prediction. The summary of the latest experiment will be given in the first half of my talk, especially focusing on the method to control the unthermalized o-Ps.

The measurements of the HFS have been performed in 1970s and 80s with the an accuracy of 3.5 ppm, and these results were consistent with each other and with the 2nd order calculations. Recently the 3rd and 4th order calculations can be performed with the new method (Non-Relativistic approximation), it turns out that there is discrepancy (3.5 σ) between the QED prediction(green band) and the previous measurements (arrows) as shown in the right figure. There are two possible systematic uncertainties in the previous all experiments:



(1) the unthermalized o-Ps contributes to underestimation of the material effect as already shown in the decay rate measurements.

(2) The uncertainties of the magnetic field which was the most significant error in the previous experiments. HFS was not directly measured in the previous experiments. The energy shift due to the Zeeman effect was measured and converted into HFS. Accuracy and homogeneous of the magnetic field was essential in the previous experiments.

We propose new methods to measure the HFS directly without these systematic uncertainties, and this is the second half of my talk.

Tests of *CP* and *CPT* symmetry with positronium

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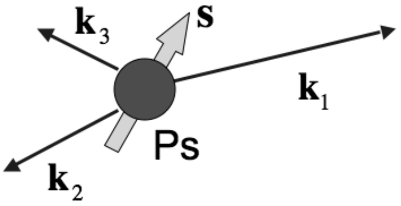

Figure 1: The 3γ decay of the triplet positronium. $\mathbf{s}$ is the positronium spin, $\mathbf{k}_n$ are the momenta of the 3γ's ($|\mathbf{k}_1| > |\mathbf{k}_2| > |\mathbf{k}_3|$).

The 3γ decay of spin-aligned triplet positronium can be used to test the *CP* (*C*=charge conjugation, and *P*=parity operation) invariance in the lepton sector. The *CP* violating angular correlation, $(\mathbf{s} \cdot \mathbf{k}_1)(\mathbf{s} \cdot \mathbf{k}_1 \times \mathbf{k}_2)$, is measured for this test, where $\mathbf{s}$ is the positronium spin and $|\mathbf{k}_1| > |\mathbf{k}_2| > |\mathbf{k}_3|$ are the γ momenta (Fig. 1) [1].

In this talk, we will show our new detector design to investigate *CP* asymmetry with an uncertainty of $\sim 10^{-3}$, which is about 10 times higher sensitivity than a previous experiment [2]. In our setup, a $^{22}\mathrm{Na}$ source is used to supply positrons, and positroniums are created in silica aerogel. For the spin alignment of the positroniums, a magnetic field of approximately 3.5 kG is applied. LYSO scintillators are used as the γ-ray detectors to obtain good energy and timing resolutions. All the detectors are rotated around the positronium source for the cancellation of the systematic errors. The detailed setup and the current status of our experiment will be reported.

We also discuss a test of the *CPT* (*T*=time reversal) invariance which can be tested with a similar setup. In this *CPT* test, another angular correlation, $\mathbf{s} \cdot (\mathbf{k}1 \times \mathbf{k}2)$, is measured [3, 4].

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Positronium molecules and many-positron systems

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The ability to accumulate and store large numbers of positrons in Penning-Malmberg traps [1] has proved to be of great utility in a number of experimental endeavours, most notably the production of Antihydrogen [2] and measurements of positron scattering from atoms and molecules at very low energies [3]. By rapidly dumping positron plasmas stored in such a trap we have been able to produce intense, sub-ns, positron bursts with instantaneous currents of more than 10 mA [4]. By implanting these positron bursts into suitable targets, positronium atoms may be created that have a chance of interacting with each other, and in this way we have begun to study systems containing more than one positronium atom, and in particular interactions between positronium atoms. So far we have observed the formation of molecular positronium (Ps_2) on the internal surfaces of porous silica [5] and on a clean Al(111) surface [6] as well as spin exchange quenching between (oppositely polarized) ortho-positronium atoms [7]. The main objective of our research, however, is to produce an ensemble of spin polarised positronium atoms at a much higher density, where they might undergo a phase transition and form a Bose-Einstein condensate at an experimentally realistic temperature (i.e., over ~ 10K) [8]. Here we shall discuss the methods used to perform our experiments, the results we have obtained so far, and what we intend to do next.

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The Quenching of ortho-Positronium

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Ortho-Positronium (o-Ps), which self-annihilates into 3γ with a lifetime of 142ns, may be quenched through various interactions with other atoms or molecules. The long lifetime of o-Ps, compared with that of para-positronium (p-Ps), is attributed to the triplet spin state of the former. Thus o-Ps is quenched when the positron in the o-Ps somehow annihilates with an electron of the opposit spin into 2γ.

The quenching of o-Ps may be classified into several cases:

(i) pick-off quenching [1]
(i) spin conversion quenching through electron exchange with:
    a molecule with non-singlet spins such as O_2 [2]
    a radical on a solid surface [3]
    a conduction electron on metal surface
(iii) spin conversion quenching through spin-orbit interaction with a heavy atom [4, 5]
(iv) chemical quenching [6]

In this report these processes are overviewed.

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Plasma Tools for Antimatter Physics

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Techniques will be described to create, manipulate and store positron plasmas in Penning-Malmberg traps in new regimes of parameter space and to create finely focused positron beams [1]. Positron plasmas are compressed radially using rotating electric fields [the so-called "rotating wall" (RW) technique], in the case where the plasma is cooled by cyclotron radiation in a strong magnetic field (B = 5 tesla) [2-4]. A regime of RW operation will be described in which the application of a fixed RW frequency, f_{RW}, spins the plasma up until the plasma rotation frequency f_{E} (i.e., which is proportional to the plasma density, n) is approximately equal to f_{RW}. This provides the ability to create a rigidly rotating plasma with a known and constant high density, $n = f_{\mathrm{E}}B/\mathrm{ce}$ (e.g., 3×10^{10} cm^{-3} for $f_{\mathrm{E}} \approx f_{\mathrm{RW}}$ = 10 MHz). To access this regime, the plasma must be driven away from states localized near "zero-frequency modes" in which n is limited by drag torques due to trap imperfections. The criteria for accessing this regime, a model of the compression process, and possible limits of this technique will be discussed [3, 4].

Studies will also be described to extract beams of small spatial extent from the plasma center [5, 6]. For small-amplitude pulses, the radial beam profile is Gaussian with a beam radius of $2\lambda_{\mathrm{D}}$ (HW to 1/e), where λ_{D} is the Debye screening length. The fraction of the plasma that can be extracted in this manner is $N_{\mathrm{b}}/N \leq 0.1(2\,\lambda_{\mathrm{D}}/R_{\mathrm{p}})^2$, where R_{p} is the plasma radius, and N is the number of positrons [6]. A model of the radial beam profiles for larger beams will be presented.

Finally, a multicell trap will be described that is designed to store orders of magnitude more positrons than is currently possible (e.g., $N > 10^{12}$) [7, 8]. Plasmas will be stored in multiple Penning-Malmberg traps ("cells"), arranged both along and in parallel off the magnetic axis. An enabling technique to move plasmas across the magnetic field using autoresonant diocotron-mode excitation will be described as well as outstanding challenges in the next steps toward development of such a trap [8].

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Antiproton Compression and Radial Measurements

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The current generation of antihydrogen ($\overline{\mathrm{H}}$) experiments aims to trap $\overline{\mathrm{H}}$ atoms as this is likely necessary for precision CPT and gravity tests. Neutral $\overline{\mathrm{H}}$ atoms have a small permanent magnetic moment, and can be trapped in a magnetic minimum. Traps based on this effect are called Minimum-B traps. To trap both charged and neutral species simultaneously, the Minimum-B and Penning-Malmberg traps must be co-located. The compatibility of Minimum-B and Penning-Malmberg traps remains controversial, but it is clear that the two are most compatible if the antiprotons ($\overline{\mathrm{p}}$'s) and positrons (e^+'s) are held close to the trap axis where the perturbations from the Minimum-B fields are smallest.

Here we report measurements of the radial extent of the $\overline{\mathrm{p}}$ clouds, and a method to compress these clouds to very small radii. We use two methods to measure the radial extent. The first is based on a micro-channel plate (MCP) and phosphor screen, and provides an image of the $\overline{\mathrm{p}}$'s similar to that shown in Fig. 1. Apertures limit the size of the plasma that we can measure to about 1.5 mm. The second uses the time history of the loss of particles when our octupole magnet is turned on to reconstruct the outer radial profile. (The octupole is used to generate the radial minimum-B fields required for our $\overline{\mathrm{H}}$ trap.) This diagnostic can measure the $\overline{\mathrm{p}}$ profile between about 7 mm and the trap wall. Using these diagnostics to determine the $\overline{\mathrm{p}}$ radius, we have successfully compressed our $\overline{\mathrm{p}}$ plasmas down to radii as small as about 0.3 mm, and increased their density by a factor of ten. We compress the $\overline{\mathrm{p}}$'s by applying a rotating electrostatic field to the electron (e^-) plasma used to cool the $\overline{\mathrm{p}}$'s. This sort of field is well known to compress particles trapped in Penning-Malmberg traps. In our case, the compressing e^- appears to drag the $\overline{\mathrm{p}}$'s with them, resulting in a compressed $\overline{\mathrm{p}}$ cloud.

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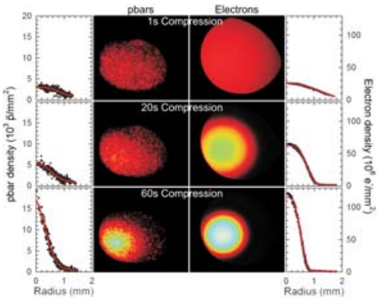

Figure 1: $\overline{\mathrm{p}}$ and e^- images showing the effects of compression, and the resulting radial profiles.

Electrons Confined with an Axially Symmetric Magnetic Mirror Field

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When a non-neutral electron plasma was confined with an axially symmetric magnetic mirror field, it was found that a confinement time was longer than 50 ms with the mirror ratio R ~ 5 [1]. This is two orders of magnitude longer than the confinement time of ~ 100 μs reported in reference [2] where the magnetic mirror field was used to accumulate low energy positrons. Since the details of the accumulation method have not been reported so far, it is worth performing the systematic investigation of the low energy charged particle accumulation with a magnetic mirror field. It is true that the confinement time obtained with a simple magnetic mirror trap is not long enough for the effective accumulation of charged particles. The original idea in the present experiment is that electrostatic potentials are applied to the magnetic mirror field to obtain a longer confinement time.

Here, electron beams with a current of 10 ~ 200 pA and energies less than 8 eV were injected into a magnetic mirror trap and accumulated inside it by applying the electron cyclotron resonance heating. By introducing electrostatic potentials, a longer accumulation was made possible.

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Ionization of Noble Gases by Charged-Particle Impact

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Charged-particle impact-ionization of noble gases has been investigated for many decades. Experimentally, much work has been done on electron collisions, but advances in the generation of intense positron beams has made such experiments possible for positron impact as well [1]. Experiments for heavy-ion impact, such as C^{6+} on He, have recently yielded very surprising results [2], and now experiments with anti-protons are underway [3]. The latter type of experiment is very appealing to theorists, since the reaction channels of positronium formation and charge exchange do not have to be considered.

Computational methods to attack this problem are generally classified as either perturbative, i.e., based upon the Born series, or non-perturbative, i.e., based the close-coupling expansion. For positron impact, the former includes work by Campeanu *et al.* [4] for direct ionization and by Gilmore *et al.* [5] for positronium formation, while positronium formation was also calculated in the coupled static-exchange approximation by McAlinden and Walters [6].

Over the past years, we have developed a general computer code [7] for charged-particle impact ionization of arbitrary atoms and ions, based upon the original work by Bartschat and Burke [8]. In this method, the projectile is described by a distorted wave while the initial bound state and the interaction between the residual ion and the ejected electron is described by an R-matrix (close-coupling) expansion. It is now possible to account, at least approximately, for second-order effects in the projectile−target interaction [9]. Such effects have been shown to be very important in highly correlated processes such as ionization plus simultaneous excitation [10] or electron-impact ionization in “out-of-plane” kinematics [11].

After summarizing the basic ideas of the computational model, we will present results for direct ionization of the noble gases He, Ne, Ar, Kr, and Xe by positron impact and compare the results with those for electron projectiles. We are currently developing a heavy-particle impact theory *beyond* the plane-wave approximation for the projectile. This method will make it possible to account for distortion effects on the heavy particle, which might be responsible for the surprising effects seen in experiments such as [2].

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Antiprotonic helium and CPT invariance

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Recent progress is reviewed in the laser spectroscopy of antiprotonic helium atoms ($\overline{\mathrm{p}}\mathrm{He}^+ \equiv \mathrm{e}^- - \overline{\mathrm{p}} - \mathrm{He}^{++}$) performed at CERN's Antiproton Decelerator facility (AD) by the ASACUSA Collaboration [1, 2]. Laser transitions were induced between Rydberg states (n, ℓ) and $(n \pm 1, \ell - 1)$ of $\overline{\mathrm{p}}\mathrm{He}^+$ ($n \sim 40$ and $\ell \lesssim n - 1$ being the principal and orbital angular momentum quantum numbers of the antiproton orbit).

Comparison of experimental (ν_{exp}) and theoretical [3] (ν_{th}) frequencies for seven transitions in $\overline{\mathrm{p}}^4\mathrm{He}^+$ and five in $\overline{\mathrm{p}}^3\mathrm{He}^+$ yielded an antiproton-to-electron mass ratio of $m_{\overline{\mathrm{p}}}/m_e = 1836.152674(5)$. This agrees with the known proton-to-electron mass ratio at the level of $\sim 2 \times 10^{-9}$. The experiment also set a limit on any *CPT*-violating difference between the antiproton and proton charges and masses, $(Q_{\mathrm{p}} - |Q_{\overline{\mathrm{p}}}|)/Q_{\mathrm{p}} \sim (m_{\mathrm{p}} - m_{\overline{\mathrm{p}}})/m_{\mathrm{p}} < 2 \times 10^{-9}$ to a 90% confidence level (Fig. 1). If on the other hand we assume the validity of *CPT* invariance, the $m_{\overline{\mathrm{p}}}/m_e$ result can be taken to be equal to m_{p}/m_e. This can be used as an input to future adjustments of fundamental constants.

Further improvements in the experimental precision would be possible if the thermal Doppler broadening could be reduced. With a near-resonant two-photon excitation method, currently being developed, it appears possible to determine the antiproton-to-electron mass ratio with a precision comparable to that of the proton-to-electron mass ratio ($\sim 0.5 \times 10^{-9}$).

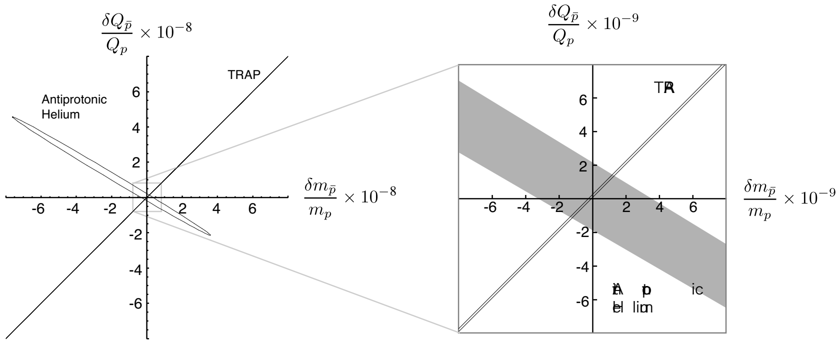

Figure 1: Limits on the difference of mass and charge between proton and antiproton. The charge/mass (Q/M) ratio was measured by the TRAP group [4] whereas $M \cdot Q^2$ by ASACUSA [5]. With the improvement of the experimental technique the allowed region was step-by-step reduced: the present limit is 2 ppb (2×10^{-9}).

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Determination of the antiproton-to-electron mass ratio by high precision spectroscopy of $\bar{p}$He^{+} atoms

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ASACUSA collaboration has carried out a laser spectroscopy of antiprotonic helium atoms ($\bar{p}\mathrm{He}^{+}$: a Coulomb three-body system consisted of an antiproton, electron, and a helium nucleus) at CERN's Antiproton Decelerator facility (AD)[1, 2] and measured transition frequencies of $\bar{p}\mathrm{He}^{+}$. By comparing the measured frequencies with three-body QED calculations, the antiproton-to-electron mass ratio $m_{\bar{p}}/m_{e}$ is determined. In 2002, we used a radiofrequency quadrupole decelerator to stop the antiprotons in low density targets and to eliminate a collisional effect with surrounding helium atoms, and determined $m_{\bar{p}}/m_{e}$ at a level of 10^{-8}. An experimental resolution had mainly been dominated by the linewidth of commercial pulsed dye lasers.

In 2004, we prepared a new laser system to achieve better experimental resolution as follows[3]. A continuous-wave Ti : sapphire or dye laser with the linewidth of 1 or 4 MHz were locked to a femtosecond optical frequency comb with a frequency precision of $< 4 \times 10^{-10}$. The cw laser light was then amplified with a linewidth of ~ 60 MHz in dye cells pumped by a pulsed Nd : YAG laser. A frequency chirp, which was caused by changes in the refractive index of the dye, was actively compensated by using an electron-optic modulator. A residual chirp was measured and corrected by recording a heterodyne beat signal between the amplified laser pulse and a 400 MHz-shifted cw laser light. With the new laser system we improved a fractional precision on the transition frequencies from $\sim 3 \times 10^{-6}$ to $\sim 1 \times 10^{-8}$.

The comparison of the measured frequencies and three-body QED calculations yields the antiproton-to-electron mass ratio of $m_{\bar{p}}/m_{e} = 1836.152\ 674(5)$. This agrees with the known proton-to-electron mass ratio at the level of $\sim 2 \times 10^{-9}$. A limit on any *CPT*-violating difference between the antiproton and proton charges and masses was also set as $(Q_p - |Q_{\bar{p}}|)/Q_p \sim (m_p - m_{\bar{p}})/m_p < 2 \times 10^{-9}$ to a 90 % confidence level.

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The Hyperfine Stuctrure of Antiprotonic Helium and the Antiproton Magnetic Moment

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The ASACUSA collaboration is performing laser and microwave spectroscopy of antiprotonic helium ($\overline{\mathrm{p}}\mathrm{He}^+$), a metastable three-body system consisting of a helium nucleus, an antiproton and an electron, at the Antiproton Decelerator (AD) of CERN. $\overline{\mathrm{p}}\mathrm{He}^+$ exhibits a hyperfine splitting (HFS) which is unique due to the large angular momentum of the metastable states ($L_{\bar{p}} \approx 35$): the HFS consists of a dominant splitting caused by the interaction of $L_{\bar{p}}$ with the electron spin S_e and a smaller splitting due to the interaction of the antiproton magnetic moment $\mu_{\bar{p}}$ with the other moments. The hyperfine splitting has been measured for the first time in 2001 with a precision of 3×10^{-5} [1]. The two observed transitions are in agreement with QED calculations at a level of 6×10^{-5}, which corresponds to the theoretical accuracy. The agreement gives a limit on the antiproton *orbital g*-factor of $\left|g_l^{\bar{p}} - 1\right| < 6\times10^{-5}$ [2]. The difference of the two transition frequencies is directly related to the value of the *spin* magnetic moment $\mu_{\bar{p}}$, which so far is known to only 0.3%. ASACUSA has started a new measurement with the goal of increasing the experimental precision by an order of magnitude, which would lead to a determination of $\mu_{\bar{p}}$ to 0.1%.

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Conclusions from recent pionic–atom experiments

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A precise method to determine the low–energy pion–nucleus interaction is to measure the level shift and broadening by means of ultimate–resolution X–ray spectroscopy. The techniques developed together with an underlying low–energy approach of QCD – chiral perturbation theory – allow the extraction of strong–interaction quantities at the per cent level [1]. The ground–state level shift and broadening in pionic hydrogen are directly related to fundamental parameters of the pion–nucleon interaction, the isospin scattering lengths $a^{\pm}$ and the πN coupling constant. Constraints on these scattering lengths are obtained from a measurement of pionic deuterium level shift. The deuterium level broadening provides an independent access to s–wave pion absorption and production on nucleon pairs. The build up of the pion's interaction with few nucleon systems is studied in measurements of the helium isotopes.

The experiments were performed at the Paul Scherrer Institut (PSI), Switzerland, using a high–resolution crystal spectrometer equipped with a large–area CCD array for position–sensitive X–ray detection. The cyclotron trap II provides a high stop density which is essential for an efficient formation of exotic atoms. Several measurements at various target densities and for different X–ray transitions have been performend in pionic hydrogen and deuterium to quantify or identify cascade effects, which must be considered for an unambiguous extraction of the hadronic effects. Data taking has been supplemented by a study of muonic hydrogen in order to determine directly the Doppler broadening from the acceleration of exotic hydrogen during the atomic cascade (Coulomb de–excitation) which hinders the direct extraction of the hadronic broadening from the line width citepsas2006.

Because of the absence of suitable X–ray standards in the few keV range, a new approach was used for the determination of the spectrometer response. With a dedicated electron cyclotron resonance ion trap (ECRIT) [3] narrow X–rays from helium–like argon, chlorine, and sulphur have been produced at high rate, which allows a precise characterisation of the spherically bent Bragg crystals.

First results from the pionic–atom experiments are presented. The techniques are briefly discussed in view of the forthcoming low–energy antiproton facilty FLAIR. There, similar experimental techniques may be applied to antiprotonic atoms in order to extract hadronic affects unambiguously at a level of accuracy comparable to the achievements in pionic atoms.

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Search for double-strangeness production in pbar-p annihilation at CERN/AD

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Weise [1] and Kienle [2] discussed recently the possibility to produce and study double-strange nuclei with stopped antiproton annihilation reaction on light nuclei, like:

$$\text{p} + \text{pbar} \rightarrow K^- + K^- + K^+ + K^+$$

The detection of two kaons in antiproton annihilation at rest in a nuclear target is an excellent signature to unravel the existence of such bound nuclear clusters, like:

$$\text{pbar} + {}^4\text{He} \rightarrow K^+ + K^+ + \text{pnn}K^-K^-$$

It would be very exciting to produce and study “double-strange nuclei” in view of the prediction of Akaishi and Yamazaki that double-antikaon bound nuclear systems with strangeness (S = -2) will be formed, with binding energies up to 400 MeV. Such binding energies might result in an increase of the average density to more than 3 times the average nuclear density. If such dense (S = -2) clusters are formed, conditions in the phase diagram might be reached where phase transition to kaon condensation or colour superconductivity occurs at low temperature.

A first hint that double-antikaon clusters were formed was found in a new analysis of the OBELIX data [3].

In the following, an experimental setup will be described to search for the existence of such exiting states using a gaseous helium target and a TPC with GEM readout. To perform the experiment at the CERN/AD will be an excellent choice, having slow pbar extraction made available by the Musashi trap.

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Interactions of laser-cooled atoms in a high-magnetic-field atom trap

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We are investigating highly magnetized, cold Rydberg-atom gases and magnetized plasmas. In our experiments, we use a particle trap that operates at magnetic fields up to 6 Tesla and that can simultaneously function as a ground-state atom trap, Rydberg-atom trap and nested Penning ion and electron trap. Ground-state ^{85}Rb atoms that have been laser-cooled and collected in the trap are laser-excited into clouds of magnetized Rydberg atoms or cold plasmas. The combination of low temperatures, strong magnetic fields, and substantial collision rates leads to a rich variety of atomic and plasma processes, such as Rydberg-atom-electron collisions and three-body recombination. Our studies relate to the physics of atoms and plasmas in astrophysical environments, in magnetized man-made plasmas, and in anti-hydrogen research.

Recently, we have demonstrated the trapping of a strongly-magnetized two-component cold plasma of ^{85}Rb$^+$-ions and electrons in a nested Penning trap at a background field of 2.9 T, particle densities up to 10^7cm^{-3}, and particle numbers up to 10^6. Electrons remained trapped in this system for several milliseconds. The trap loss results from $\mathbf{E} \times \mathbf{B}$ drift, and is well understood. Early in the evolution, the dynamics are driven by a breathing-mode oscillation in the ionic charge distribution, which modulates the electron trap depth. The modulation in electron-trap depth causes a periodic electron “shake-off” signal, which can be observed. The shake-off signal exhibits reproducible structures that develop with increasing density; we believe that these structures are a manifestation of plasma waves. Over longer time scales, the electronic component undergoes significant cooling; the origin of the electron cooling is under investigation.

At higher Rydberg-atom or plasma densities, collisions and / or recombination lead to the formation of atoms in gyration-center states, which exhibit distinct cyclotron, bounce and magnetron motions of the Rydberg electron. These drift-state atoms have large z-components of the angular momentum, high densities of states, and long lifetimes. They are well-suited for magnetic trapping, as has recently been demonstrated in this project. Trapped Rydberg atoms can be used to measure atomic properties such as polarizabilities, cyclotron quantum numbers, and decay rates.

In studies of low-angular-momentum Rydberg atoms directly excited by high-resolution lasers, we are interested in coherent single-atom dynamics and in coherent interactions in many-body Rydberg-atom systems. Coherent effects of the internal motion include spin oscillations of the Rydberg electron induced by spin-orbit coupling. We report on our first high-resolution ($<$ 5MHz linewidth) spectroscopic studies of laser-cooled atoms in strong magnetic fields, at energies below and above the absolute photo-ionization threshold.

Rydberg Atom Formation in Cold (Anti)plasmas

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In 2002 the ATHENA and ATRAP collaborations have reported the first production of cold antihydrogen atoms at CERN. Subsequently several properties of these exotic atoms and characteristics of their formation dynamics could be probed – both being crucial for the success of furture cooling and trapping of the created atoms.

In this talk, I will present results of extensive Monte-Carlo calculations describing the formation of highly excited antihydrogen atoms in strong magnetic fields. It will be demonstrated that the internal and translational state distribution observed in ATRAP's experiments can be consistently explained if all relevant collision processes are properly taken into account.

Based on these results, I will identify general properties of collisionally formed Rydberg atoms and present semi-classical calculations of their long-time dynamics in the inhomogeneous fields of strong atom-traps. Implications for prospects of future trapping experiments will be discussed.

Giant Dipole States of Single-Electron and Multi-Electron Systems in Crossed Electric and Magnetic Fields

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The origin and physics of giant dipole states for both single-electron and multi-electron systems is reviewed. First an outline of the gauge-independent pseudoseparation of the center of mass motion of moving neutral atomic systems in crossed electric and magnetic fields is provided. As a result a generalized potential picture [1] is derived and discussed in some detail. The double well structure of this potential leads to the existence of weakly bound decentered Rydberg states that possess a huge electric dipole moment: The giant dipole states. The spectral properties of these states is analyzed and linked to the underlying classical dynamics and phase space [2]. An experimental preparation scheme starting from ground state atoms, employing subsequent laser excitation and a sequence of electric field pulses is described. Corresponding simulations yield a well-defined population of low-energy states in the outer potential well [3]. We demonstrate that the crossed field configuration provides a unique way for stabilizing simple matter-antimatter systems [4, 5]. Calculations on positronium predict the existence of long-lived giant dipole states of the e^+/e^- system in which the two particles are separated by several thousand Angstroms. The near zero probability for positron-electron overlap suppresses direct annihilation processes. Transition moments between the ground state in the outer well and the Coulomb states are also extremely small, resulting in lifetimes up to the order of one year.

Multi-electron giant dipole resonances of atoms in crossed electric and magnetic fields [6] are addressed in a next step. Stationary configurations corresponding to a highly symmetric arrangement of the electrons on a decentered circle are derived, and a normal-mode and stability analysis are performed. A classification of the various modes, which are dominated by the magnetic field or the Coulomb interactions, is provided. Based on the MCTDH approach, we carry out a six-dimensional wave-packet dynamical study for the two-electron resonances, yielding in particular lifetimes of more than 0.1μs for strong electric fields [7, 8].

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Atomic Physics Research with Highly Charged Ions and Exotic Nuclei at the Future FAIR Facility

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An overview about the envisioned program of the research collaboration (Stored Particle Atomic Research Collaboration, http://www.gsi.de/sparc) at the future GSI accelerator facility will be given. This program exploits the key features of the future international accelerator that offer a range of new and challenging opportunities for atomic physics and related fields [1].

In SPARC we plan experiments in two major research areas: collision dynamics in strong electromagnetic fields and fundamental interactions between electrons and heavy nuclei up to bare uranium. In the first area we will use heavy ions up to the relativistic energies for collision studies. With the extremely short, relativistic enhanced field pulses, the critical field limit (Schwinger limit) for lepton pair production can be surpassed by orders of magnitudes. Complementary to the relativistic collision regime, at low ion energies the atomic interactions are dominated by strong perturbations and quasi-molecular effects. Here even investigations of the super-critical field regime will be possible.

The cooler ring NESR a "second-generation" ESR will have optimized features and novel installations. This unique facility will allow for a broad range of experimental studies ranging from single ion decay spectroscopy to experiments exploiting highest beam intensities for accurate x-ray spectroscopy of atomic transitions in the heaviest one- and two-electron ions. These experiments will focus on structure studies of selected highly-charged ion species, a field that is still largely unexplored; with determinations of properties of stable and unstable nuclei by atomic physics techniques on the one hand, and precision tests of quantum electrodynamics (QED) and fundamental interactions in extremely strong electromagnetic fields on the other hand. Different complementary approaches will be used such as relativistic Doppler boosts of optical or X-UV laser photons to the X-ray regime, or coherent radiation by channelling of relativistic ions, or electron-ion recombination, or electron and photon spectroscopy that will give hitherto unreachable accuracies. These transitions can also be used to laser-cool the relativistic heavy ions to extremely low temperature. Another important scenario for this class of experiments will be the slowing-down, trapping and cooling of particles in the ion trap facility HITRAP. There high-accuracy experiments in the realm of atomic and nuclear physics will be possible [3].

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Particle Physics Techniques in Cold Antimatter Studies

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Antimatter studies often involve detection of high energy radiation from the annihilations. Techniques developed for particle physics experiments can be applied in order to detect, characterize and diagnose antimatter processes. In this talk, we will discuss some of these techniques, with particular emphasis on the detection system in the ALPHA experiment at CERN.

A Particle Physicist looks at Global Warming

John Eades

University of Tokyo

Paul Roberts, Journalist, on Global Warming, in *The End of Oil* :

Whereas one might hope after 20 years of scientific and political debate to see the outlines of an action plan, climate policy has instead stalled in a mind-numbing blame game in which governments, corporations and advocacy groups argue over who is most at fault for past emissions, who should cut future emissions, and who should pay for it all -- while the collective gaze of the global public glazes over in boredom and incomprehension.

Most physicists surveying media coverage of this topic would agree. However the purpose of the media is to tell an interesting story, not to present detailed scientific evidence. Consequently, contrarian, alarmist and controversial views are often given equal time, even when their scientific basis is demonstrably weak. The literature on this complex subject being indeed highly specialized, it is not easy to explain to newspaper readers and TV viewers. However, much of the physics behind global warming is a familiar part of a particle physicist's general background. In evaluating it, we therefore owe it to ourselves, and to those members of the general public with whom we may discuss it, to apply the same critical faculties we use in our own work.

I shall therefore try to look at this topic from a particle physicist's point of view with special reference to the many points of contact with our own discipline, and to the activities and opinions of some of our well-known colleagues.

First attempts at antihydrogen trapping in ALPHA

The ALPHA experiment is designed to trap antihydrogen atoms in a minimum-B configuration. The antihydrogen is produced by merging plasmas of positrons and antiprotons in a cryogenic Penning trap. I will describe the design and operation of the ALPHA apparatus, and I will discuss the first attempts at trapping antihydrogen in this device.

Jeffrey S. Hangst, on behalf of the ALPHA collaboration

Trapping Antihydrogen

A different mixing approach

Paul D. Bowe[1] for the ALPHA collaboration.

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The present focus of the two working antihydrogen experiments at CERN is to trap antihydrogen in multipole atom traps. The mixing method that has produced most antihydrogen to date involves injecting antiprotons as projectile particles into a positron cloud of target particles located in a so called nested trap. This scheme has several shortcomings. The states and velocities of the resulting antihydrogen are not conducive to trapping, the dynamics of the interaction are difficult to disentangle and the process may be negatively influenced by the presence of the multipole fields.
A short review will be given of what has been learned to date and an outline of a different scheme described which pulls together several new plasma physics techniques which have been developed recently both without[1] and within the ALPHA collaboration. An effort will be made to underline how this new approach may help to avoid some of the difficulties of the classic nested trap.

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Antihydrogen Production in Positron Beam Ion Trap

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The electron beam ion trap (EBIT) is widely applied for an accumulation of heavy ions such as Uranium and various atoms. For various fundamental research of antimatter world a production of antihydrogen is the exact starting point. Among many proposals for making an antihydrogen beam EBIS like ion production will obviously open a new physics in next era of anti-world.

With advent of new technologies such as high energy photon source, positron production is not so difficult as to generate an intense beam which could produce a deep positive potential for storing a large number of antiprotons. Since the successful experiments on the synthesis of antihydrogen atoms performed on the LEAR antiproton storage ring at CERN, fundamental physics research has been continued so far and ASACUSA project has made a progress in atomic and elementary particle physics as well as a theoretical physics of QED world. In order to investigate more precisely by using much more antimatter we should cope with several technological difficulties for its production. The positron beam ion trap might be a great step to expand the antimatter world. This will be a introduction of a proposal for making the highest rate of the antihydrogen production[1,2].

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Measurement of the Ground-State Hyperfine Splitting of Antihydrogen

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The hydrogen atom is one of the most extensively studied atomic systems, and its ground state hyperfine splitting (GS-HFS) of $\nu_{\mathrm{HFS}} \simeq 1.42$ GHz has been measured with an extremely high precision of $\delta\nu_{\mathrm{HFS}}/\nu_{\mathrm{HFS}} \sim 10^{-12}$. Therefore the antimatter counterpart of hydrogen, the antihydrogen atom, consisting of an antiproton and a positron, is an ideal laboratory for studying the CPT symmetry.

A consistent extension of the standard model by Kostelecký *et al.* [1] introduces parameters into the Lagrangian of the standard model which violate either the CPT symmetry or the Lorentz invariance. These parameters have a dimension of energy (or frequency). Therefore by measuring a relatively small quantity on the energy scale (like the 1.42 GHz GS-HFS), a smaller relative accuracy is needed to reach the same absolute precision for a CPT test. This makes a determination of ν_{HFS} with a relative accuracy of 10^{-4} competitive to the measured relative mass difference of 10^{-18} between K^0 and $\overline{K^0}$, which is often quoted as the most precise CPT test so far.

The ASACUSA collaboration at CERN's Antiproton Decelerator (AD) has recently submitted a proposal [2] to measure ν_{HFS} of antihydrogen in an atomic beam apparatus similar to the ones which were used in the early days of hydrogen HFS spectroscopy. The apparatus will use antihydrogen atoms produced either in a superconducting radiofrequency Paul trap or in a superconducting cusp trap (i.e. anti-Helmholtz coils). In the former case, the apparatus would consist of two sextupole magnets for the selection and analysis of the spin of the antihydrogen atoms, and a microwave resonator to flip the spin. In the latter case, the first sextupole could be omitted because the cusp trap should be able to provide a partially polarized antihydrogen beam. This atomic beam method has the advantage that antihydrogen atoms of temperatures up to 150 K can be used.

Status of the preparations for the experiment will be presented in the talk. Numerical simulations will also be presented which show that such an experiment is feasible if $\sim$100 antihydrogen atoms per second can be produced in the ground state, and that an accuracy of better than 10^{-6} can be reached within reasonable measuring times.

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Cryogenic Particle Accumulation for ATRAP Antihydrogen Experiments

Cody Storry

York University

ATRAP antihydrogen experiments continue to advance toward our eventual goal of producing large numbers of antihydrogen atoms for trapping and a spectroscopic comparison between matter and antimatter. Antihydrogen atoms are made from their charged constituents (positron and antiprotons) confined within a cryogenic Penning trap. Antihydrogen will be trapped in an Ioffe trap consisting of a radial quadrupole magnetic field with increased axial field at the ends from aligned coils. To allow for trapping of a significant fraction of antihydrogen produced the strength of the axial magnetic field for charge particle confinement must be reduced. This reduced Penning trap magnetic field brings new challenges for charged particle confinement and cooling in the Penning trap.

In spite of these challenges our ATRAP collaboration has increased the number of charge particles for antihydrogen production and produced atoms in the magnetic fields from the Ioffe trap. Positron from a 22Na radioactive source are accumulated in a room temperature Penning trap, accelerated by electric fields, guided by magnetic fields and enter from above into the cryogenic apparatus for antihydrogen production. Antiprotons are produced in collisions with high energy protons from the accelerators at CERN incident on a target. These particles are slowed in CERN's antiproton decelerator and are provided in bunches of 30 million particles every 100 seconds. These particles enter our cryogenic apparatus from below and are further slowed as they pass through a degrader foil within the cryogenic apparatus. For further cooling to cryogenic temperatures both antiprotons and positrons are cooled by collisions with electrons in separate Penning trap wells.

In this talk I will describe the techniques used for accumulation of antiprotons, positrons and cooling electrons which have lead to our resent antihydrogen production within the magnetic field gradient for eventual antihydrogen trapping.

Solid-state continuous Lyman-alpha source for laser-cooling of antihydrogen and the prospect of antihydrogen gravity measurements

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Andreas Müllers, and Martin Scheid

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Future high-resolution laser-spectroscopy of antihydrogen in a magnetic trap can provide very stringent tests of the fundamental symmetry between matter and antimatter (CPT symmetry). The extremely narrow 1S–2S two-photon transition is an excellent candidate for such experiments. However, the 1S–2S ($F = 1, m_F = 1 \rightarrow F = 1, m_F = 1$) transition frequency at 2466 THz has a residual dependence on the magnetic field of 186 kHz per Tesla. This will broaden and shift the spectral line of antihydrogen atoms in a magnetic trap. It will thus be very important to cool antihydrogen atoms, thereby reducing their spatial spread in the inhomogeneous magnetic field of the trap.

Laser cooling of antihydrogen to the milli-Kelvin temperature range can be done on the strong Lyman-alpha transition at 121.6 nm wavelength from the 1S ground state to the 2P excited state. Continuous coherent four-wave mixing can be used to generate radiation at Lyman-alpha. For this process, three laser-beams at 254 nm, 408 nm, and 545 nm wavelength generate a beam at the sum-frequency, using mercury vapor as a nonlinear optical medium.

At Mainz we are setting up a new continuous-wave coherent Lyman-alpha source which is based on solid-state laser-systems. The beam at 254 nm is generated by frequency-quadrupling the radiation of an Yb:YAG disk-laser in two enhancement cavities. Output powers of up to 1 W have been generated. The beam at 408 nm will come from frequency-doubling the radiation of a Titanium:Sapphire laser in an enhancement cavity. The beam at 545 nm is generated by frequency-doubling the radiation of an Yb fiber-laser in an enhancement cavity. Output powers of up to 4 W have been produced. The talk will discuss the status of the new Lyman-alpha source.

In addition to testing CPT at unprecedented levels of experimental precision with antihydrogen there is also the exciting chance to measure the gravitational acceleration of antihydrogen for the first time. Ultracold temperatures in the sub-millikelvin range are desirable for practical experiments. These temperatures are beyond standard laser-cooling limits for (anti-)hydrogen and ideas to cool antihydrogen atoms to ultracold temperatures will be discussed.

Antihydrogen production

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Antihydrogen production in ATHENA [1] is analyzed more carefully. The most important peculiarities of the different experimental situations are discussed. The protonium production via the first matter-antimatter chemical reaction is commented too [2,3]. The most recent data from the ALPHA, ATRAP and ASACUSA Collaborations at the AD (CERN) are discussed [4].

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Laser ionization of muonium for low-energy muon source

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We have been developing a low-energy muon source at RIKEN-RAL muon facility [1,2]. Polarized muon beam has been used as a unique and powerful tool to investigate magnetic properties or spin fluctuation of materials using a technique called μSR [3]. The kinetic energy of muons available for such purpose at accelerator facilities like ISIS, TRIUMF and PSI is 4 MeV or above. This determines the stopping range of muon in a solid to typically a few tenths of mm or above. Our goal is to extend the scope of the μSR technique to nano-scale system like thin film, multi-layers, and inter-layers by providing a polarized muon beam whose kinetic energy can be varied from a few eV to a few tens keV. Our method to generate such beam is based on the fact that a large fraction of muons stopped in a heated tungsten film are re-emitted into a vacuum as muonium (μ^+e^-) atoms [4]. By ionizing muonium atoms, we obtain polarized muons which have thermal energy of around 0.2eV. We then accelerate them to desired energy in an electrostatic field in order to control their implantation depth.

The essential to this method is an efficient way for ionizing muonium atoms. For that purpose, we have developed a pulsed laser system which generates Lyman-α radiation to excite a muonium atom from 1S ground state to 2P state. The muonium atom is then ionized from 2P state by a 355nm photon generated as a third harmonic of an Nd:YAG laser. The Lyman–α photon is generated using a four-wave sum-difference frequency mixing technique in Kr gas.

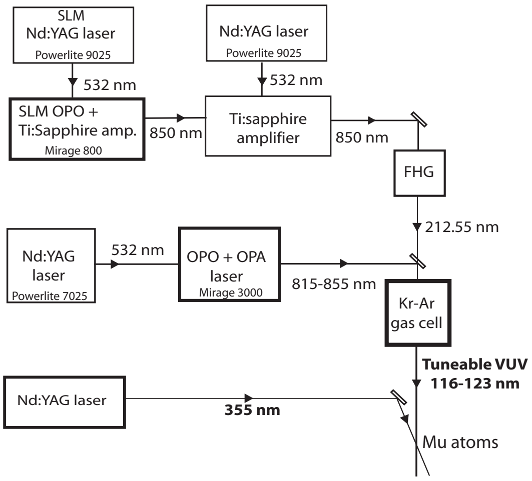

Figure 1: Schematic of the laser system

Currently we observe around 15 low-energy muons per second. Overall efficiency to convert 4-MeV muon beam to 10-keV muon beam is around 3x10^{-5}, which is about same as the other method developed at PSI [5]. We anticipate large increase of the conversion efficiency in the future, as we see no sign of saturation of muon yield as laser power increases.

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Ionization of noble gas atoms in slow antiproton collisions

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In order to improve our understanding of the physics of atomic collisions, accurate experimental data are needed which can be used as benchmarks for the development of advanced calculations of these dynamically developing many-body systems. One of the simplest processes in this field is the single ionization of helium by antiproton impact. Here, there is a strong many-body effect, namely the electron-electron correlation, but on the other hand there is no complication from electron transfer. Furthermore the projectile is heavy which means that it moves in a classical orbit and that we can investigate ionization in collisions where the projectile moves with a speed much slower than that of the target electrons. At CERN's LEAR we measured the total cross sections for single and multiple ionization of a multitude of targets for impact of antiprotons with velocities down to that of the outer electrons in the targets [1,2]. This in turn led to the development of more than a dozen advanced theories. These calculations coalesce at high projectile speed, bur shown great spread a low projectile energies. In order to judge the validity of these models, we therefore need to measure ionization for impact of antiprotons of a few keV.

Using a new technique for the production of intense beams of very slow antiprotons [3] developed by the ASACUSA collaboration at CERN's AD facility, we have been able to obtain accurate cross sections for single ionization of helium and single and double ionization of argon down to impact energies of 3 keV [4]. In this talk, I will present the technique and the results and compare them to the theoretical calculations.

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A new time-dependent scattering theory: application to the capture of antiprotons by hydrogen atoms and helium atoms

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We developed a time-dependent scattering theory [1, 2] to study a general Coulomb three-body scattering problem in the low collision energy region. The working equation of the theory

$$|\Psi^+(0) >= -i \int_{-\infty}^{0} e^{i(E-H+i\eta)t} V|\Psi_0 > dt + |\Psi_0 >,$$

which is equivalent to the formal time-independent scattering equation, provides an intuitive physical picture. To solve the above equation numerically, we (1) discretize the space in the pseudo-spectra grid, in which we can put denser grids in the inner region; (2) use an energy-dependent absorber to filter out the outgoing wavepacket in the outer region smoothly; (3) propagate the wave-function by the split-operator-method, which makes the problem solvable with a reasonable computation afford. By this *non-perturbative full quantum* method, we studied the state-specified capture process of antiprotons by hydrogen atoms, which was not solved by any other method. Figure 1 shows the cross sections of the antiproton captured to the (n, ℓ) states at 2.72 eV and 10 eV incident energies. For the lower incident energy (2.72 eV), the antiproton is mainly captured to the highest possible n ($n = 33$) from the energy conservation and highest possible ℓ. For the higher incident energy (10eV), the antiproton is captured to a broad region in the n, ℓ-space. The detailed numerical method and the comprehensive results will be presented in the workshop. The preliminary results of the capture cross section of antiprotons by helium atoms will also be presented.

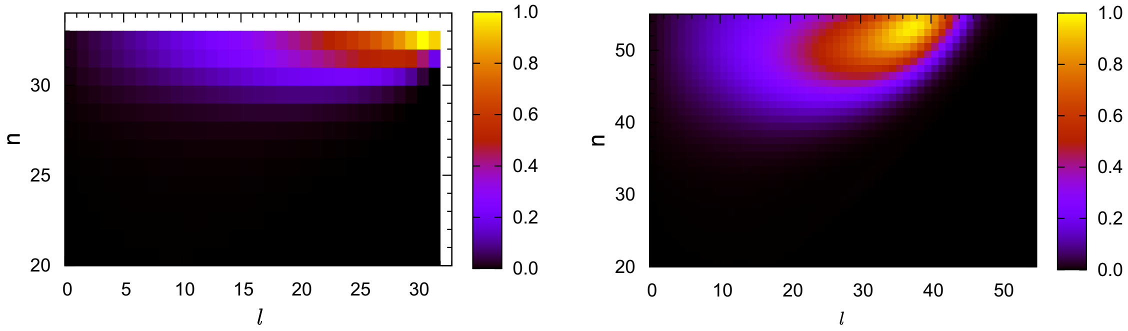

Figure 1: The state-specified (n, ℓ) capture cross sections of antiprotons by hydrogen atoms at 2.72 eV (right) and 10.0 eV (left) incident energies in the center of mass frame.

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Atomic Collision Experiments with Ultra-Low-Energy Antiprotons

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We have developed a Monoenergetic Ultra-Slow Antiproton Source for High-precision Investigation (MUSASHI) over the last several years [1]. The ultra-slow antiproton beam which can now be extracted stably has opened up the possibility to study ionization and atomic capture processes between an antiproton and an atom “A”,

$$\bar{\mathrm{p}} + \mathrm{A} \rightarrow \bar{\mathrm{p}} + \mathrm{A}^+ + \mathrm{e}^- \quad \text{and} \quad \bar{\mathrm{p}} + \mathrm{A} \rightarrow (\bar{\mathrm{p}}\mathrm{A}^+)^0 + \mathrm{e}^-$$

at an unprecedented low energy under the single-collision condition for the first time [2]. The collision energy can be tuned from 10 eV to 1 keV either by varying the beam transport energy or by biasing the voltages at the collision region.

Since the number of available antiprotons is very much limited, the reaction probability must be maximized in order to make best use of them. We have prepared a powerful supersonic helium gas jet with a density of 3×10^{12} atoms/cm^3 to be crossed with the antiproton beam [3]. For rigorous identification of particles (e^-, $\bar{\mathrm{p}}$ and $(\bar{\mathrm{p}}\mathrm{A}^+)^0$) needed for reduction of huge background signals, we developed a detection system with two microchannel plates each with a delay-line two-dimensional position sensitive detector, and a box of scintillator plates. A set of electrodes and coils were placed near the collision point to guide electromagnetically the electrons perpendicular to the antiproton beam. The reaction events will be recognized by an electron signal followed by an antiproton annihilation with an appropriate time of flight.

Our design and strategy of the experiment as well as our preliminary results will be presented in the talk.

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Observation of Ultra-Slow Antiprotons with Micro-Channel Plate

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Our group ASACUSA-MUSASHI has succeeded in accumulating several million antiprotons and extracting them as monochromatic ultra-slow antiproton beams (10 eV-1 keV) at CERN AD [1]. Recently, we have performed atomic collision experiments [2] and have obtained some preliminary results to be presented in another talk of this workshop [3]. In these experiments, we have observed some unexpected background signals decaying on the various time constants triggered by the antiproton annihilations using micro-channel plates (MCP). The integrated pulse area of the output signals generated when the MCP was irradiated by ultra-slow antiprotons was 6 times higher than that by electrons. As a long-term effect, we also observed an increase in the background rate presumably due to the radioactivation of the MCP surface. We focus in the present study on these unexpected events accompanying ultra-slow antiprotons detection. One of the distinct features of the new monochromatic ultra-slow antiproton beam is extremely short range of the antiprotons in matter. Irradiating the antiproton beams on the MCP induces antiproton-nuclear annihilations only on the first layer of the surface. Low-energy and short-range secondary particles like charged nuclear fragments caused by the "surface nuclear reactions" would be the origin of our observed phenomena. In the talk, the observation of ultra-slow antiprotons in recent experiments from the viewpoint of the "surface nuclear reactions" will be discussed.

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Sub-Femtosecond Correlated Dynamics Probed with Antiprotons

J. Ullrich, M. Grieser, R. von Hahn, K.U. Kühnel, R. Moshammer, C.D. Schröter,
C.P. Welsch

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Whereas the three-body Coulomb problem for single excitation and ionization has claimed to be solved for the first time in a mathematically correct way during 1999 until 2004 for electron impact on hydrogen and helium, ion-impact ionization still represents a major challenge for theory. Troubling discrepancies have been observed recently in fully differential cross sections (FDCS) for He single ionization by fast ion impact and even experimental total cross sections are in striking disagreement with the predictions of all state-of-the-art theories for low-energy antiproton collisions.

For antiprotons at energies below about 300 keV down to 1 keV the interaction time between the projectile passing atoms or molecules is on the order of 80 attoseconds (as) up to 1 femtosecond (fs) and, thus, comparable to the revolution time of outer-shell electrons in atoms or molecules. Since ionization or excitation is the only reaction channel that can occur for antiprotons, and electron energies would be below the threshold at similarly low velocities, slow antiprotons provide an unsurpassed, precise and the only tool to study many-electron dynamics in the strongly correlated, non-linear, sub-femtosecond time regime, the most interesting and, at the same time, most challenging domain for theory.

Exploiting and developing many-particle imaging methods – reaction-microscopes – in combination with novel electrostatic storage rings for slow antiprotons we envision to perform, for the first time, single and multiple ionization cross section measurements for antiprotons colliding with atoms, molecules and clusters. Total, as well as any differential cross sections up to FDCS including ionization-excitation reactions will become available serving as benchmark data for theory. Several theory groups world wide concentrate efforts to solve the fundamental few-body Coulomb problem for heavy-particle and antiproton impact. Moreover, the formation of antiprotonic atoms, molecules or of protonium might be explored in kinematically complete experiments at ultra-low energies yielding unprecedented information on (n, l)-distributions of captured antiprotons as well as precise spectroscopic data of the respective energy levels.

In order to achieve these goals, challenging developments in both, storing and imaging techniques have been launched at MPI-K. A novel ultra-low energy storage ring (USR) to be integrated at the proposed facility for low-energy antiproton and ion research (FLAIR) will be developed for electron-cooled antiprotons in the energy range between 300 keV and 20 keV possibly even approaching the sub keV regime. A reaction microscope shall be integrated in the ring thus achieving unprecedented luminosity. Recently a fully equipped in-ring reaction microscope has been operated for the first time successfully in the Experimental Storage Ring (ESR) at GSI and is now further improved at the Test Storage Ring (TSR) in Heidelberg.

In the talk, the present status of experiments in comparison with theory will be highlighted and the layout of envisioned machines at FLAIR, the USR with an integrated as well as single-pass reaction microscope, will be presented.

Low-energy scattering of antihydrogen by helium and molecular hydrogen

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The experimental work at CERN on antihydrogen ($\bar{\text{H}}$) has focussed attention on interactions involving $\bar{\text{H}}$.

The first calculations we carried out were on $\text{H}\,\bar{\text{H}}$ scattering at very low energies [1,2].

We are in the process of calculating cross sections for the three rearrangement reactions

$$\text{He} + \bar{\text{H}} \to \text{He}^+\bar{p} + Ps \text{ or } \text{He}\bar{p} + \text{e}^+ \text{ or } \alpha\bar{p} + Ps^-$$

at very low energies. These cross sections are simply related to the T-matrix

$$T_{fi} = \langle \Phi_f | V_f | \Psi^{(+)}_{\mathbf{k}_i} \rangle,$$

where $\Psi^{(+)}_{\mathbf{k}_i}$ is the exact scattering wave function for the incident energy under consideration. V_f is the potential that couples the two systems resulting from the scattering, e.g. $\text{He}^+\bar{p}$ and Ps. Φ_f is the final wave function if V_f is set to zero.

As in ref. [2], the exact scattering wave function was approximated by the wave function for the entrance channel, calculated using the Born–Oppenheimer (BO) approximation.

The leptonic wave function for the incident channel was calculated very accurately using basis functions, χ_i, of the form

$$\chi_i = \left(\frac{1}{2\pi}\right)^{\frac{3}{2}} [\lambda_1^{a_i}\lambda_2^{b_i}\lambda_3^{c_i}\mu_1^{d_i}\mu_2^{e_i}\mu_3^{f_i} \times \exp(-\alpha_1\lambda_1 - \alpha_2\lambda_2 - \alpha_3\lambda_3 + \beta_1\mu_1 + \beta_2\mu_2 + \beta_3\mu_3) S(p_i) + 2 \leftrightarrow 3]$$

where particle 1 is the positron, 2 and 3 are the electrons, λ_i and μ_i are prolate spheroidal coordinates for particle i, $a_i, \ldots, f_i$ are non-negative integers, $\alpha_1, \ldots, \beta_3$ are non-linear parameters and $2 \leftrightarrow 3$ indicates the corresponding exchange term. Depending on the value of p_i in $S(p_i)$, χ_i is a σ or π type CI function or a Hylleraas-type function. Both positron-electron and electron-electron correlation are taken into account.

The continuum wave function for the relative motion of the He and the $\bar{\text{H}}$ was calculated using the BO potential of Strasburger et al. [3]. Very accurate or exact wave functions were used for the systems in the rearrangement channels. A description of this work at an earlier stage is given in ref. [4]. The latest results for the rearrangement cross sections for all three reactions will be reported at the conference.

In addition, a description will be given of a preliminary calculation on $\text{H}_2 - \bar{\text{H}}$ scattering [5].

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Annihilation and rearrangement in atom-antihydrogen collisions

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Recently the ATHENA and ATRAP groups at CERN managed to produce antihydrogen atoms at low temperatures [1]. Future goals of these experiments are to trap the antihydrogen atoms and perform spectroscopic measurements comparing antihydrogen with ordinary hydrogen. Such measurements can test the CPT theorem for baryons and leptons.

The new experimental progress has also stimulated interest in low temperature atom-antiatom collisions. Such collisions have several properties that make them qualitatively very different from ordinary atom-atom collisions. One obvious difference is that in the Coulombic nucleus-antinucleus interaction is attractive. Hence, the nucleus and antinucleus have a finite probability of overlapping in an atom-antiatom collision. Therefore it is necessary to include the strong nuclear force between the nucleus and antinucleus. The strong nuclear force leads both to annihilation processes and to a change in the elastic cross section.

I will discuss how the strong nuclear force may be incorporated in calculations of low-energy antihydrogen-atom scattering. In particular I will discuss a scattering-length method, which has been applied to antihydrogen-hydrogen and antihydrogen-helium scattering [2, 3, 4].

Another important class of inelastic channels is rearrangement, in which the oppositely charged nuclei form a bound system, possibly also binding one or more of the electrons. The excess energy is carried off by the positron and the remaining electrons. In the case of low-temperature hydrogen-antihydrogen scattering, calculations show that rearrangement into positronium and protonium (the bound state of a proton and an antiproton) has a rate comparable to the rate for direct annihilation.

A difficulty in rearrangement calculations is the existence of a critical internuclear separation, below which the leptons are no longer bound to the nuclei. In particular I will focus on the antihydrogen-proton (or hydrogen-antiproton) system, which is the simplest system possessing a critical distance. For this system the critical distance $R_c = 0.639a_0$ was found as early as 1947 [5]. I will give a new analytical result for the binding energy of the electron/positron for $R \gtrsim R_c$. I will also show that the Born-Oppenheimer approximation breaks down as $R \rightarrow R_c$. This problem can be cured by explicitly including rearrangement channels through an optical potential [6]. I will present low-energy rearrangment cross sections calculated using this method.

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Status and opportunities of FLAIR

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The future accelerator facility for beams of ions and antiprotons at Darmstadt [1] will provide antiproton beams of intensities that are two orders of magnitude higher than currently available. Within the foreseen scheme, antiprotons can be decelerated to 30 MeV. The low-energy antiproton community has formed a users group to make use of this opportunity to create a next-generation low-energy antiproton facility called FLAIR. A letter of intent [2] has been submitted for a new facility that goes far beyond the current Antiproton Decelerator at CERN by providing cooled antiproton beams using two storage rings of 300 keV and 20 keV minimum energy. The availability of low-emittance beams at these low energies will greatly enhance the density of antiprotons stopped in dilute gases or ion traps for precision spectroscopy. FLAIR will also provide slow extracted (i.e. continuous) beams of antiprotons, thereby enabling nuclear and particle physics type experiments which need coincidence techniques. Using internal targets in the storage rings, atomic collision experiments with ultra-low energy antiprotons and ions can be performed for the first time.

The letter of intent for FLAIR as well as the technical proposal [3] have been positively evaluated by the APPA PAC and the STI committee of FAIR, and FLAIR has been added to the core part of FAIR. If funding can be secured, FLAIR will provide antiproton and ion beams from the year 2014. After the official start of the FAIR project in November 2007, the efforts towards realizing FLAIR have to be enforced. The current status of the project and the necessary steps towards its realization will be reviewed.

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