CONFERENCE
LOW ENERGY ANTIPROTON
PHYSICS
Mars 12 - 16th 2018
Sorbonne Université, Jussieu Campus,
Paris-France
Organizers

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Proceedings

The proceedings will be published in Hyperfine Interaction. The paper from LEAP 2018, once accepted will appear immediately on the journal. There will be a separate topical collection that will regroup all papers from LEAP.

The papers will be freely available for one year, and then will require a regular subscription to the journal. There will be no paper copies provided.

More info on http://leap2018.lkb.upmc.fr/
**Welcome:**

*Sorbonne Université*

Gautier Hamel de Montchenault (CEA)

Patrice Verdier (CNRS-IN2P3)

Antimatter in Space (P. von Balmoos)

Cindy Cirelli

ELENA (C. Carli)


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**Welcome drink and registration:** Pierre et Marie Curie university.

Seminar room of IMPMC, Tower #23, 4th floor, hallway 22-23, room 401

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**HITRAP (M. Vogel)***

**Contribution**

14:00-14:20: Angela Gligorova

14:20-14:40: Egle Tomasi-Gustafsson

14:40-15:00: Elena Vannuccini

15:00-15:20: Bernadette Kolbinger

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**LEAP 2018 time table**

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**Conference dinner 19:30**

La Coupole

102 Boulevard du Montparnasse, Paris

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**Visits (Sorbonne Crystal collection)**

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**Conference dinner 19:30**

La Coupole

102 Boulevard du Montparnasse, Paris
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Talks

Monday 12\textsuperscript{th}
Antimatter in Space

Peter von Ballmoos

Institut de Recherche en Astrophysique et Planétologie
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Balloon and satellite experiments detect antimatter in the Universe both directly, as a cosmic ray component, and indirectly, through characteristic annihilation signatures.

Positrons: For over five decades positrons have been studied in cosmic rays, just as long as we have been observing them through the 511 keV gamma-rays they emit when annihilating. The question on their origin, however, is still far from being settled, neither for the high-energy cosmic ray positrons, nor for the positrons annihilating in the central regions of our Galaxy. Nevertheless, the most plausible scenarios for their production all involve processes occurring at the endpoints of stellar evolution.

Baryonic antimatter: During forty years, direct detection of baryonic antimatter has essentially concerned the measurement of antiprotons, naturally produced in cosmic ray interactions with the interstellar medium. Recently, the tentative detection of a few 3He by AMS has revitalized the discussion on the existence of baryonic antimatter in the Universe. Since revoking an MeV bump hinted in the seventies, gamma-ray astronomy has more and more constrained the fraction of antimatter possibly contained in astrophysical objects. The absence of characteristic annihilation features on all scales has virtually ruled out the existence of substantial quantities of antimatter in the visible Universe.
Antiproton Flux and Antiproton-to-Proton Flux Ratio in Primary Cosmic Rays Measured with the AMS on ISS

Zhi-Cheng Tang

1. Institute of High Energy Physics, Chinese Academy of Sciences

Precision measurements by AMS of the antiproton flux and the antiproton-to-proton flux ratio in primary cosmic rays in the absolute rigidity range from 1 to 450 GV are presented based on $3.49 \times 10^5$ antiproton events. At $\sim 20$ GV the antiproton-to-proton flux ratio reaches a maximum. Unexpectedly, above 60 GV the antiproton spectral index is consistent with the proton spectral index and the antiproton-to-proton flux ratio shows no rigidity dependence in the rigidity range from $\sim 60$ to $\sim 500$ GV. This unexpected observation requires new explanation of the origin of cosmic ray antiprotons.
Can we expect a difference in the trajectories of particles and antiparticles in a gravitational field? Surely, since the Equivalence Principle is central to General Relativity, it seems that any such difference must be vanishingly small in GTR. On the other hand, Scherk [1] showed that supergravity with $N = 2$-8 generators lead to antigravity. Using arguments developed by Philip Morrison [3], Hermann Bondi [3], Richard Price [4], Tsvi Piran [5] and others, I will show that a simple modification of the expression of the Equivalence Principle would lead to antigravity, as observed in the analog system of electrons and holes in a semiconductor [6].

Also, using the recent demonstration that negative mass solutions are allowed in a de Sitter spacetime [7], I describe the counter-intuitive polarisation and levitation effects that occur in General Relativity when bound systems of positive mass and negative mass particles are considered [4]. This will lead us to the Dirac-Milne universe [8], a universe that, unlike the standard Λ-CDM model, and without any free parameter, is impressively concordant, without requiring Dark Matter and Dark Energy. I will also briefly describe the three experiments at CERN, ALPHA-g, AEgIS and Gbar, aiming at the sensitivity of antigravity and beyond on antihydrogen atoms.

References

Cosmological structure formation with negative mass

G. Manfredi, J.-L. Rouet, B. Miller, G. Chardin

1. Université de Strasbourg, CNRS, IPCMS UMR 7504, F-67000 Strasbourg, France.
2. Université d’Orléans, CNRS/INSU, BRGM, ISTO, UMR7327, F-45071 Orléans, France.
3. Department of Physics and Astronomy, Texas Christian University, Fort Worth, TX 76129, USA.

While cosmological structure formation with negative mass objects may seem initially strange, the possibility that particles with negative mass exist has long been considered [1–3], starting from the seminal work of H. Bondi [4]. More recently, Paranjape and Mbarek have shown that negative mass solutions are viable in a de Sitter universe [5]. Besides, we cannot but note the strangeness of the Standard Cosmological Model, which – although impressively concordant on primordial nucleosynthesis, CMB, BAO and SN1a luminosity distance – features a very strange composition, with Dark Matter and Dark Energy, two unidentified components, supposedly representing approximately 96% of the Universe content.

In this context, Benoit-Lévy and Chardin [6] have recently proposed a symmetric matter-antimatter universe, analog of the electron-hole system in a semiconductor, where antimatter particles have a negative gravitational mass. The Dirac-Milne universe appears as gravitationally empty (or coasting) at large scales, and is remarkably concordant without any adjustable parameter.

In order to explore such alternative cosmological scenarios, we construct a family of Newtonian non-relativistic models with equal amounts of negative and positive gravitational mass particles, which includes as a special case the Dirac-Milne scenario. We perform N-body simulations of these negative-mass models for an expanding one-dimensional universe and study the associated formation of gravitational structures, focusing in particular on the Dirac-Milne case. The differences and analogies with the standard cosmological model are highlighted and discussed.

References

CPT violation, Lorentz violation, and low-energy antiprotons

Arnaldo J. Vargas

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The Standard-Model Extension (SME) is an effective field theory that extends the standard model of particle physics and general relativity by incorporating Lorentz- and CPT-violating operators of arbitrary mass dimension. Experimental collaborations searching for deviations from CPT symmetry can benefit from using models derived from the SME. Using these models the experimental groups can identify the type of CPT-violating terms they are testing, quantify their findings as bounds on these CPT-violating operators, and compare the sensitivity of their results with other experimental collaborations around the world. In many cases the main experimental signal for CPT violation targeted by the collaborations is only sensitive to a limited set of CPT-violating terms and with the help of the SME the experimental groups can identify other experimental signals that are sensitive to different sets of CPT-violating terms maximizing the impact of their experiment. The SME models also indicate that the if CPT symmetry is broken then it is possible for signals for Lorentz violation to be enhanced in antimatter experiments compared to ordinary matter experiments. This observation suggests that antimatter experiments could lead to a better understanding of gravity at the quantum level because Lorentz violation is considered a possible low-energy signal for candidate quantum gravity theories. In this talk the main features of SME models for different experimental scenarios such as antimatter spectroscopy experiments, antiproton Penning-trap experiments, muon spin-precession experiments, and antimatter gravity tests will be discussed.
The BASE Collaboration Review and Outlook

S. Ulmer\(^1\), A. Mooser\(^1\), C. Smorra\(^{1,2}\), S. Sellner\(^1\), M. Bohman\(^{1,3}\), M. J. Borchert\(^{1,4}\), J. A. Harrington\(^3\), T. Higuchi\(^{1,5}\), G. Schneider\(^{1,6}\), M. Wiesinger\(^{1,3}\), K. Blaum\(^3\), Y. Matsuda\(^5\), C. Ospelkaus\(^4\), W. Quint\(^7\), J. Walz\(^{6,8}\), Y. Yamazaki\(^1\)

\(^1\) RIKEN, Ulmer Fundamental Symmetries Laboratory, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan, \(^2\) CERN, 1211 Geneva, Switzerland, \(^3\) Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, D-69117 Heidelberg, Germany, \(^4\) Leibnitz Universität, Welfengarten 1, D-30167 Hannover, Germany, \(^5\) Graduate School of Arts and Sciences, University of Tokyo, Tokyo 153-8902, Japan, \(^6\) Institut für Physik, Johannes Gutenberg-Universität D-55099 Mainz, Germany, \(^7\) GSI Helmholtzzentrum für Schwerionenforschung GmbH, D-64291 Darmstadt, Germany, \(^8\) Helmholtz-Institut Mainz, D-55099 Mainz, Germany

The Baryon Antibaryon Symmetry Experiment (BASE-CERN) at CERNs antiproton decelerator facility is aiming at high-precision comparisons of the fundamental properties of protons and antiprotons, such as charge-to-mass ratios, magnetic moments and lifetimes. Our single-particle multi-Penning-trap experiments provide sensitive tests of the fundamental charge-parity-time invariance in the baryon sector. BASE was approved in 2013 and has measured since then the antiproton-to-proton charge-to-mass ratio with a fractional precision of 69 p.p.t. [1], as well as the antiproton magnetic moment with fractional precisions of 0.8 p.p.m. [2] and 1.5 p.p.b. [3], respectively. At our matter companion experiment BASE-Mainz, we have performed proton magnetic moment measurements with fractional uncertainties of 3.3 p.p.b. [4] and 0.3 p.p.b. [5]. By combining the data of both experiments we provide a baryon-magnetic-moment based CPT test

\[
\frac{g_{\bar{p}}/2}{g_p/2} = 1.000\ 000\ 000\ 2(15),
\]

which improves the uncertainty of previous experiments [6] by more than a factor of 3000. A unique antiproton reservoir trap used in BASE furthermore allows us to set constraints on directly measured antiproton lifetime [7]. Our current value \(\tau_{\bar{p}} > 10.2\) a improves previous best limits by a factor of 30. In this talk I will review the achievements of BASE and focus on recent developments which will allow us to further reduce our measurement uncertainties.

A ppb measurement of the antiproton magnetic moment

C. Smorra\textsuperscript{1} on behalf of the BASE collaboration

\textit{1. RIKEN, Ulmer Fundamental Symmetries Laboratory, 2-1 Hirosawa, Wako-shi, Saitama, JAPAN, 351-0198}

The high-precision comparisons of proton/antiproton properties carried out in the advanced multi Penning-trap system of the BASE experiment challenge the CPT symmetry in the Standard Model of particle physics, since any deviation in proton and antiproton properties would hint to yet uncovered CPT-odd interactions that would act differently on matter and antimatter-conjugates.

We recently reported a measurement of the antiproton magnetic moment with 350-fold improved precision [1, 2]. To this end, we store single antiprotons in a multi-Penning trap system and measure the frequency ratio of the Larmor frequency to the cyclotron frequency, the frequency ratio providing the magnetic moment of the antiproton in units of the nuclear magneton. Our recent measurement uses a novel multi-trap two-particle scheme, which enhances the data accumulation rate compared to the established double-trap method. We use one particle at about 350 K energy in the radial modes to measure the cyclotron frequency and an ultra-cold particle with less than 200 mK energy for the detection of individual spin-transitions to probe the Larmor frequency. This method became possible by reducing parasitic energy fluctuations during the adiabatic transport of the Larmor particle to less than 22 mK per cycle. In this way, we improved the relative uncertainty of the antiproton magnetic moment to 1.5 ppb uncertainty (68 \% C.L.) [1]. The result is in agreement with our measurements of the proton magnetic moment [3, 4] and supports CPT invariance up to an energy resolution of $10^{-24}$ GeV.

In my presentation, I will present the observation of individual antiproton spin transitions [5], which are absolutely essential for multi-trap methods, and our latest multi-trap magnetic moment measurement [1].

Figure 1: Spin-flip resonance of the antiproton $g$-factor measurement with 1.5 ppb resolution.

References

The CERN Antiproton Decelerator AD provides antiproton beams with a kinetic energy 5.3 MeV to an active users community. The experiments typically capturing the antiprotons in traps would profit from a lower beam energy, as this would allow them to improve the capture efficiency. However, with the given AD circumference, it is not possible to significantly reduce the extraction energy of this machine. The Extra Low Energy Antiproton ring (ELENA) is a small synchrotron with a circumference of 30.4 m, a factor 6 smaller than the AD, to further decelerate antiprotons from the AD from 5.3 MeV to 100 keV. Controlled deceleration in a synchrotron equipped with an electron cooler to reduce emittances in all three planes will allow the existing AD experiments to increase substantially their antiproton capture efficiencies and render new experiments possible. A status report on the ELENA project and, in particular, on progress of ring commissioning using 100 keV H⁻ beams from an external source and antiprotons from the AD will be given.

ELENA

C. Carli on behalf of the AD and ELENA teams

1. CERN
Prospects of FLAIR, the Facility for Low-energy Antiproton and Ion Research

Eberhard Widmann

1. Stefan Meyer Institute for Subatomic Physics, Austrian Academy of Sciences, Boltzmannagasse 3, 1090 Vienna, Austria

With the construction of FAIR, the Facility for Antiproton and Ion Research at Darmstadt, gaining momentum, it becomes timely to discuss again the opportunities for physics with low-energy antiprotons at FAIR. FLAIR as defined in the Baseline Technical Report in 2005 [1] consisted of two storage rings, a magnetic Low-energy Storage Ring LSR and an electrostatic Ultra-low energy Storage Ring USR, and the HITRAP facility. The core features of FLAIR are the simultaneous use of the facility for low-energy antiprotons and highly charged ions, and the availability of both fast and slow extracted antiprotons at energies down to 20 keV as well as at rest in HITRAP. FLAIR, together with the NESR storage ring needed for deceleration, is not part of the phase 1 of FAIR and thus its realisation is currently unclear. Nevertheless, significant progress has been made in the mean time with CRYRING, which was selected as LSR by the FLAIR community, having been modified for its usage as LSR, moved to GSI/FAIR and installed behind the existing Experimental Storage Ring ESR [2]. Together with the HITRAP facility also starting operation at the ESR, two of the central components of FLAIR are now existing and will start the physics program with highly charged ions. A study was made how to bring antiprotons from the production target to the ESR in order to generate the full FLAIR facility at the current location of ESR, CRYRING, and HITRAP. The study [3] concluded that it is possible to transfer antiprotons to ESR and to decelerate them in ESR and CRYRING, producing antiproton beams of similar intensity and energy as will be available soon at CERN-AD/ELENA. The advantage of the availability of internal targets in the storage rings and slow extracted beams from FLAIR makes several experiments uniquely possible at this facility. This talk will describe the physics potential with low-energy antiprotons of FLAIR.

References

The HITRAP facility for deceleration and trapping of highly charged ions and antiprotons

M. Vogel\textsuperscript{1}, Z. Andelkovic\textsuperscript{1}, G. Birkl\textsuperscript{2}, F. Herfurth\textsuperscript{1}, H.-J. Kluge\textsuperscript{1}, W. Nörtershäuser\textsuperscript{3}, W. Quint\textsuperscript{1}, Th. Stöhlker\textsuperscript{1}, R.C. Thompson\textsuperscript{4}, G. Vorobjev\textsuperscript{1}, and the HITRAP collaboration

\textsuperscript{1}. GSI, Darmstadt, Germany
\textsuperscript{2}. Institut für Angewandte Physik, TU Darmstadt, Germany
\textsuperscript{3}. Institut für Kernphysik, TU Darmstadt, Germany
\textsuperscript{4}. Imperial College London, London, UK

The HITRAP facility at GSI, Darmstadt, Germany, is designed for deceleration and cooling of highly charged ions from energies of several MeV to 4 K and subsequent low-energy transport to a number of experimental stations \cite{1,2,3}. To this end, it features a series of deceleration stages and a cryogenic Penning trap in which the particles are cooled by electron cooling and resistive cooling. This talk will present the outline of the facility, its status, and briefly look at the Penning-trap experiments ARTEMIS, SPECTRAP and HILITE currently located at HITRAP. Also, possibilities for experiments with low-energy antiprotons in the framework of FAIR (Facility for Antiproton and Ion Research), currently under construction, will be discussed.

![Figure 1: Schematic of the current HITRAP facility.](image)

References

\cite{1} H.-J. Kluge et al., HITRAP: A facility at GSI for highly charged ions, Advances in Quantum Chemistry \textbf{53} (2007) 83.
\cite{2} Z. Andelkovic et al., HITRAP - a facility for experiments on heavy highly charged ions and on antiprotons, Journal of Physics: Conference Series \textbf{194} (2009) 142007.
Talks

Tuesday 13\textsuperscript{th}
PUMA: a trap project for antiprotons and short-lived nuclei

Alexandre Obertelli

Institut für Kernphysik
Technische Universität Darmstadt

Antiprotons as probe for nuclear studies with short-lived isotopes remain unexploited despite past pioneer works at CERN/LEAR and Brookhaven. Antiprotons offer a very unique sensitivity, as a probe, to the ratio of neutron and proton densities at annihilation site, i.e. in the density tail of the nucleus. The project officially started on January 1st, 2018. Its motivations and concept will be presented.
Search for polarized antiproton production

D. Grzonka et al.

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Polarization observables allow the extraction of more detailed information of the structure of hadrons and their interaction and the disentangling of various reaction mechanisms is often only possible by a separation of different spin configurations. For antiprotons possible methods for polarization are discussed since the first antiproton beams became available [1] but up to now there is no simple procedure for the preparation of a polarized antiproton beam. The actual favored solution is the spin filter method where a stored unpolarized antiproton beam is polarized by passing through a polarized target. The technique in principle works as shown with protons but it is rather effortful [2]. A quite simple procedure for the generation of a polarized antiproton beam could be worked out if antiprotons are produced with some polarization.

In order to investigate this possibility measurements of the polarization of produced antiprotons have been started at CERN. Secondary particles produced with the PS beam were transferred in a beam line adjusted to 3.5 GeV/c momentum to the detection system sketched in Fig.1. It included a liquid hydrogen analyzer target, tracking detectors, scintillators, a Cherenkov detector to veto the dominant pion background and a DIRC for the particle identification. The polarization will be determined from the asymmetry of the elastic antiproton scattering in the CNI region for which the analyzing power is well known. Details on the experiment and the ongoing data analysis are given in [3][4] and the references cited therein.

Figure 1: Sketch of the detection system used for the antiproton polarization study.

References
ATRAP, located at CERN’s Antiproton Decelerator (AD), is unique among the experiments at the AD - it has both octupole and quadrupole magnets in its nested Penning-Ioffe trap, it is a vertical apparatus where the antiprotons enter from the bottom of the apparatus and positrons enter from the top. The positrons are accumulated from a Na-22 source (located 6m away) and are guided through magnetic transfer lines to the trap. The pbar catching efficiency is increased with the help of a field boosting solenoid (2.7T), which can be turned on and off in addition to the background 1T field, giving roughly 100,000 antiprotons per shot and can get up to a few million by stacking several shots. Electron clouds are used for cooling the antiprotons and positrons. ATRAP has four radial and an axial access ports for laser cooling and spectroscopy of antihydrogen, a Cesium oven for increasing the antihydrogen production rate.

In the past couple of years ATRAP suffered serious setbacks due to vacuum leaks in the apparatus which were solved in late 2016. ATRAP is again ready and back in business. The goal of this presentation is to give an overview the ATRAP experiment.
ASACUSA CUSP antihydrogen beam experiment

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The aim of the ASACUSA CUSP experiment is a stringent test of CPT symmetry through a precision spectroscopy of ground-state hyperfine structure of antihydrogen [1, 2]. We have developed an anti-atomic beam method based on the classical Rabi-type beam spectroscopy, and have already demonstrated the synthesis of antihydrogen atoms [3] and the production of an antihydrogen beam [4] with prototype apparatuses.

We have been developing a novel double-cusp trap to obtain enough number of spin-polarized ground-state antihydrogen atoms for the hyperfine spectroscopy. The double-cusp trap functions with a combination of an electrostatic potential well provided by multiple ring electrodes and a double cusp magnetic field which is an aligned configuration of two magnetic cusps by two pairs of anti-Helmholtz coils. The field configuration of the double-cusp trap sorts out spin states of antihydrogen atoms and thus provides a spin-polarized beam [5].

In this talk, an overview of the ASACUSA CUSP experiment will be presented. We will also discuss attempted various mixing schemes with the double-cusp trap to increase the production rate of antihydrogen atoms and the first measurement of quantum states of formed antihydrogen atoms [6, 7].

References

Precision measurements of magnetically trapped antihydrogen provides a unique and powerful way to test matter-antimatter symmetries. A cornerstone of the standard model, CPT symmetry demands that the spectrum of antihydrogen be identical to that of its ordinary matter counterpart. Of particular interest is the 1S-2S transition which has been measured in hydrogen[1] with the remarkable relative precision of a few parts in $10^{15}$, and promises a particularly elegant and high precision test of CPT symmetry by comparison to antihydrogen.

Recently, the ALPHA collaboration made the first observation[2] of the 1S-2S transition in antihydrogen, which put a one-sided bound on the transition frequency with a relative precision of about $2 \times 10^{-10}$ while being consistent with the hydrogen frequency.

In this talk, I will present the latest advances in 1S-2S spectroscopy in antihydrogen along with the methods developed by the ALPHA collaboration to perform spectroscopy on small samples of trapped antihydrogen atoms. Finally, I will present some of the future improvements needed to take this milestone measurement to the same precision as its hydrogen counterpart.

Figure 1: The central components of the ALPHA apparatus. All components shown to scale except for the annihilation detector, which extends to a larger radius than shown.

References

The AEGIS Antimatter Gravity Experiment

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The AEgIS experiment aims to measure the local gravitational acceleration of antimatter to make a direct test of the weak equivalence principle of General Relativity on a matter-antimatter system. The technique pursued is to create a pulsed cold antihydrogen beam through the charge-exchange reaction between antiprotons and positronium to then measure such beam’s deflection in the gravitational field of the Earth with the use of a moiré deflectometer. In this talk a general overview of the experiment and the gravity measurement technique will be given. Also, recent developments in the antimatter manipulation techniques in AEgIS will be presented with the main emphasis given to a new positron injection scheme and to antiproton and electron ballistic transfer techniques used within the main AEgIS trap system.
Status of the GBAR experiment at CERN

Bruno Mansoulié\textsuperscript{1}, on behalf of the GBAR collaboration

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The GBAR experiment aims at measuring the free-fall of antihydrogen atoms. It is located at CERN in the AD area and will be connected to the new ELENA low-energy antiproton ring. Installation of the first components has started during the second half of 2017. The status and plans of the experiment will be given in this talk.
Measuring antimatter gravitation with trapped antihydrogen: The ALPHA-g experiment

William Bertsche

University of Manchester, Manchester, UK

The ALPHA experiment is expanding its experimental program to include a dedicated instrument for measuring antimatter gravitation. We are building on our success in routine antihydrogen confinement to expand a proof-of-principle method first demonstrated in the original ALPHA apparatus to a precise measurement of antimatter gravitational acceleration. The ALPHA-g experiment will measure annihilation distributions from trapped populations of antihydrogen atoms as escape by controlled-release from our magnetic minimum trap. By measuring the antihydrogen distribution, as well as trap fields, the gravitational potential for antihydrogen atoms can be inferred. The ultimate goal for the first generation of this apparatus is to achieve a measurement of antihydrogens gravitational acceleration at the 1% level.

New in-beam measurement of the hydrogen hyperfine splitting and prospects

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2. Stefan-Meyer-Institut für subatomare Physik, der Österreichischen Akademie der Wissenschaften, Boltzmanngasse 3, A-1090, Austria

The goal of the ASACUSA-CUSP collaboration at the Antiproton Decelerator of CERN is to measure the ground-state hyperfine splitting of antihydrogen using an atomic spectroscopy beamline down to relative precisions of $10^{-6} - 10^{-7}$. A milestone was achieved in 2012 through the successful detection of 80 antihydrogen atoms 2.7 meters away from their production region. This was the first observation of “cold” antihydrogen in a magnetic field free region [1]. However, the spectroscopy measurement is currently limited by the low flux of ground state antihydrogen atoms at the exit of the formation region [2].

In parallel to the work on the antihydrogen production, the spectroscopy beamline intended to be used for antihydrogen spectroscopy was tested with a source of hydrogen. This led to a measurement at a relative precision of $10^{-9}$ which constitutes the most precise measurement of the hydrogen hyperfine splitting in a beam [3]. This measurement also enabled to forecast the necessary conditions to achieve a measurement at the ppm level with antihydrogen.

The hyperfine splitting in hydrogen reported in [3] was determined using extrapolation of one of the ground state hyperfine transitions measured at different external magnetic fields. The apparatus has since been modified to allow simultaneous measurements of two transitions which in principle allows a determination of the zero-field hyperfine splitting with less atoms; something of great interest for the antihydrogen experiment.

I will review the experimental techniques used and the latest results obtained as well as the prospects for further measurements on hydrogen using the same apparatus for tests of Lorentz symmetry.

References

Talks

Wednesday 14th
Nuclear stopping power of antiprotons

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The slowing down of energetic ions in solids is determined by the nuclear and electronic stopping powers. Both of these have been studied extensively for ordinary matter ions. For antiprotons, however, there are numerous studies of the electronic stopping power, but none of the nuclear one. Here, we use quantum chemical methods to calculate interparticle potentials between antiprotons and different atoms, and derive from these the nuclear stopping power of antiprotons in several solids. The results show that the antiproton nuclear stopping powers are much stronger than those of protons, and can also be stronger than the electronic stopping power at the lowest energies (see Fig. 1) The interparticle potentials are also implemented in a molecular dynamics ion range calculation code, which allows to simulate antiproton transmission through degrader foil materials. Foil transmission simulations carried out at experimentally relevant conditions show that the choice of antiproton-atom interaction model has a large effect on the predicted yield of antiprotons slowed down to low (a few keV) energies [1].

![Figure 1: Nuclear $S_n$ and electronic $S_e$ stopping powers of antiprotons in Si (left) and protons in Si (right).](image)

We use the simulation approach developed to simulate systematically the slowing down of 100 keV antiprotons, that will be produced in the ELENA storage ring under construction at CERN, in energy degrading foils. The results predict that the optimal foil thickness for slowing down the antiprotons from 100 keV to below 5 keV is 910 nm in Al foils [2] and 1500 nm in Si foils [1]. Also the lateral spreading of the transmitted antiprotons is reported and the uncertainties discussed.

References

Differential cross sections in collisions of low-energy antiprotons with ions and atoms

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The facility for antiproton and ion research being constructed in Darmstadt as well as the renovated facility at CERN will provide high-quality antiproton beams. This will allow to perform various collisional experiments with low-energy antiprotons. In addition, latest progress in experimental technique of the recoil-ion and electron momentum spectroscopy enables one to carry out kinematically complete experiments and measure fully differential cross sections (FDCS) for ionization in ion-atom collisions. Such cross sections contain the most complete information on ionization dynamics and provide very stringent test of theoretical models.

An experimental investigation of the FDCS in this collision is not possible at the moment. Nevertheless, the ionization cross sections have already been extensively studied theoretically by various non-perturbative methods [1, 2, 3, 4]. However, several results, obtained by these methods, considerably differ. Within our independent calculation [5], we can give preference to the results of certain approaches and resolve some discrepancies.

Besides, the Coulomb glory occurring in elastic scattering of low-energy antiprotons off ions will be reviewed. This phenomenon consists of a prominent maximum of the differential cross section in the backward direction at a certain energy of the incident antiproton, provided the interaction with a target is represented by the Coulomb attraction of the nucleus screened by atomic electrons. The effect was first predicted by Demkov and co-workers [6, 7] and further elaborated in Refs. [8, 9, 10]. Our investigations can assist in experiment designing for the first observation of the Coulomb glory in scattering of antiprotons.

References

Laser cooling of anions for ultracold antihydrogen

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For experiments studying antihydrogen – either by spectroscopy or by matter wave interferometry – it is crucial to produce ultracold anti-atoms in order to reach the highest possible precision. One of a small number of possible avenues towards this goal is the pre-cooling of antiprotons using laser-cooled anions [1]. Currently available cooling techniques for negatively charged particles allow cooling only to the temperature of the surrounding environment, typically a few kelvin. In this scheme, a fast electronic transition in an atomic anion will be used to laser-cool it to microkelvin temperatures. Ensembles of any other negative ions (including antiprotons) can then be indirectly cooled by Coulomb collisions (sympathetic cooling). Until now, there are only three known atomic anions with bound–bound electric-dipole transitions. We have investigated such transitions in two of these candidates, Os\(^{−}\) [2] and La\(^{−}\) [3,4], by high-resolution laser spectroscopy in order to test their suitability for laser cooling. The principle of the method, its potential applications, as well as recent experimental results will be presented.

References

The GBAR collaboration aims for a direct measurement of the gravitational interaction between matter and anti-matter via the free fall of single anti-hydrogen atoms in the earth gravitational field [1]. The anti-hydrogen will be produced at the ELENA/AD facility at CERN. To minimize the initial velocity distribution for the free-fall experiment the anti-hydrogen will be created in a positively charged state, consisting of one anti-proton and two positrons. This anti-ion will be trapped in a Paul trap and sympathetically cooled by co-trapped $^9\text{Be}^+$ ions. The capturing will be done in a two-stage process. In a first macroscopic capture trap with order $10^6$ beryllium ions the anti-hydrogen ions will be cooled below 100 mK. They then are transported to a precision trap and cooled below 100 µK using a single Be$^+$ ion using the elaborated laser cooling schemes developed in the ion trapping community. The mixed ion crystal will be cooled into the motional ground-state of the harmonic trap potential. To further optimize the velocity uncertainty the vertical confinement will be ramped down adiabatically keeping the ions in the ground-state [2]. A major challenge is the mass ratio of beryllium and anti-hydrogen of 9/1 causing a small coupling between the two species [3].

We report on the status of the Paul trap experiment for sympathetic cooling and adiabatic expansion. Mixed crystals of $^{40}\text{Ca}^+$ and $^9\text{Be}^+$ ions are captured in a micro-structured linear Paul trap. An improved trap construction procedure provides low heating rates, even at low trap frequencies below 200 kHz, a critical prerequisite for both, ground-state cooling and the adiabatic release of ions. We show first experimental results of mixed-crystal side-band spectra and sub-Doppler cooling. Optimized voltage ramps for decreasing the trap frequency and velocity spread guarantee a minimized heating of the ions. We discuss a new, accelerator hall approved, efficient resonant laser ionization setup for beryllium [4] and the laser system for Doppler cooling of beryllium. A new design for the trap used to first capture the anti-ions from the decelerator beam is discussed. The capture trap has to be suitable for trapping of a large number of beryllium ions in a relatively large trapping volume and needs segmentation to separate beryllium from anti-hydrogen after cooling. The lithographically contructed trap on quartz wafers [5] solves the difficulty in seperating the incoming ion beam from the axial Doppler cooling laser by introducing three trapping zones divided by a small angle. For imaging of the ion fluorescence we use a conducting, transparent ITO (indium tin oxide) layer.

References

[5] support by M. Keil and R. Fölm, Ben-Gurion University, Israel.
Lyman-α source for laser cooling antihydrogen

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We present a Lyman-α laser developed for cooling trapped antihydrogen. The system is based on a pulsed Ti:sapphire laser operating at 729 nm that is frequency doubled using an LBO crystal and then frequency tripled in a Kr/Ar gas cell. After frequency conversion, this system produces up to 5.7 µW of average power at the Lyman-α wavelength. This laser is currently operating at the CERN ATRAP experiment.
Antihydrogen formation via charge exchange
between positronium and antiproton

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Since the first synthesis of cold antihydrogen \cite{Amoretti2002}, most experiments in the same field have exploited (and substantially improved) the same technique, based on the mixing of positrons and antiprotons clouds interacting via three body recombination, with only one relevant exception \cite{Storry2004}; in this paper, the feasibility of a different way to antihydrogen production was demonstrated, via antiproton-positronium charge exchange mediated by cesium atoms, along the lines of a method first proposed in a pioneering work published in 1986 \cite{Deutch1986}.

The AEgIS experiment aims at producing antihydrogen (and eventually measuring the effects of the Earth gravitational field on it) with a similar method, based on the charge exchange reaction between antiproton ($\bar{p}$) and positronium ($Ps$):

\[
\bar{p} + Ps^* \to \bar{H}^* + e^-
\]

where positronium ($Ps$) is produced by positrons implantation on a mesoporous silica target and subsequently excited to a Rydberg state via double step laser excitation \cite{Aghion2016}.

This process can be in principle much more efficient than the traditional mixing process, because of the large cross section for Rydberg charge exchange, and has the advantage that the final $\bar{H}$ quantum states can be predicted as a function of the initial $Ps^*$ quantum states, and their distribution is relatively narrow, so that they can be accelerated by electric field gradients. Moreover, antiprotons can be preemptively cooled in order to reduce their transverse velocity and make a collimated beam of antihydrogen.

In this contribution, we will focus on Monte Carlo simulations designed for the assessment of the $Ps$ laser excitation in the antiproton Penning trap region, and then developed to give a realistic estimation of the antihydrogen production rate.

References

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\end{enumerate}
A new approach for measuring antiproton annihilation at rest with Timepix3

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Ultra precise tests of CPT (charge, parity, time) symmetry, in view of the baryon asymmetry in the Universe is the main motivation for the experiments at the Antiproton Decelerator (AD) at CERN. Most of them focus on studying antihydrogen - the only stable, neutral antimatter system available for laboratory study. Crucial to the success of these experiments is the efficient detection and correct tagging of antiprotons and antihydrogen. Mostly it is achieved with tracking detectors, through the reconstruction and extrapolation of the trajectories of charged pions produced in the annihilation process [1,2,3,4]. These detectors determine the time and position of antiproton annihilations and usually consist of layers of silicon strip modules [1,2] or scintillating bars and fibres [3,5]. We present here a different detection method, using a pixel detector, where the antiprotons annihilate inside the detector volume or in a thin foil in front of it. This approach gives high resolution on the annihilation position (tens of µm), making it dominant for experiments with such requirement [6]. When integrated with a conventional tracking detector, the method makes possible to detect and identify most of the products in antiproton-nucleus annihilation (charged pions, protons, alphas and heavy fragments). A detailed study of their multiplicity and energy distributions is essential for tuning the physics models in the Monte Carlo simulations (e.g. GEANT4) in the low-energy region. This work incorporates studies from two AD experiments, employing the Timepix3, an ASIC hybrid detector developed by CERN’s Medipix3 collaboration, characterised with high spatial resolution and nanosecond precision on the Time-of-Arrival and Time-over-Threshold [7]. Direct detection of antiprotons was performed on a dedicated beam line within AEgIS [8], providing quantitative results on the tagging efficiency and the position resolution of the annihilation point, which will be discussed [9]. The measurement of the multiplicity and energy distributions of the prongs in antiproton annihilations in different materials was set up in ASACUSA, where the information from a quad array of Timepix3 and the existing hodoscope was combined [3]. The advantages of having two detectors and a first glimpse on the results will be presented.

References

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The PANDA experiment at FAIR

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The PANDA experiment, is a core project of the future Facility for Antiproton and Ion Research (FAIR) at GSI in Darmstadt [1]. It will investigate antiproton proton annihilations on nucleons and nuclei with the aim to explore fundamental questions in the nonperturbative regime of QCD as the origine of the hadron mass. The multi-purpose detector is currently under construction. The intense and high quality anti-proton beam will span the momentum range between 1.5 and 15 GeV/c. The detection of hadrons, leptons, and photons in the final states will be possible with very high precision. A rich physics program as resonances in the charmonium and open charm region, electromagnetic form factors, hyper nuclear physics will be investigated. The worldwide collaboration gathers today more than 450 physicists from 60 institutions in 19 countries. The talk will give an overview of the PANDA experiment and of the most important aspects of the physics program. It will focus on the topics that will be investigated as soon as the facility is operational.

References

The General Antiparticle Spectrometer (GAPS) is designed to carry out a sensitive dark matter search by measuring low-energy cosmic-ray antiparticles. Below a few GeVs the flux of antiparticles produced by cosmic-ray collisions with the interstellar medium is expected to be very low and several well-motivated beyond-standard models predict a sizable contribution to the antideuteron flux. GAPS is planned to fly on a long-duration balloon over Antarctica in the austral summer of 2020. The primary detector is a $\sim 1m^3$ central volume containing planes of Si(Li) detectors. This volume is surrounded by a time-of-flight system to both trigger the Si(Li) detector and better reconstruct particle tracks. The detection principle of the experiment relies on the identification of the antiparticle annihilation pattern. Low energy antiparticles slow down in the apparatus and they are captured in the medium to form exotic excited atoms, which de-excite by emitting characteristic X-rays. Afterwards they undergo nuclear annihilation, resulting in a star of pions and protons. The simultaneous measurement of the stopping depth and the dE/dx loss of the primary antiparticle, of the X-ray energies and of the star particle-multiplicity provides very high rejection power, that is critical in rare-event search. GAPS will be able to perform a precise measurement of the cosmic antiproton flux below 250 MeV, as well as a sensitive search for antideuterons. This presentation will address the physical motivation of the experiment, discuss the current status and give an update on the payload design.
A Detector for Measuring the Ground State Hyperfine Splitting of Antihydrogen

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The combined symmetry of charge conjugation, parity and time reversal (CPT) is a pillar of the Standard Model and no violation has been found so far. As a consequence matter and antimatter are predicted to have equal or sign-opposite properties. Nonetheless the observed matter-antimatter asymmetry in the universe cannot be explained quantitatively.

The ASACUSA Collaboration at CERNs Antiproton Decelerator aims for a precise CPT test by measuring the ground state hyperfine splitting of antihydrogen. Antiprotons and positrons form antihydrogen [1] in a double CUSP trap, the antiatoms escape the trap as a beam and enter a Rabi-like spectrometer apparatus [2]. A detector records the annihilation signal at the end of the beamline. Its purpose is to count the arriving antihydrogen atoms and also distinguish signal from background events (mainly cosmics).

The detector consists of a central scintillator disk with position sensitive readout and a surrounding two layered tracking detector [3] made up of plastic scintillators with silicon photo multiplier readout. Its time resolution allows to differentiate between particles coming from inside and those traversing the detector from outside. In order to enable 3D tracking and precise vertex reconstruction, an upgrade has been implemented using scintillating fibres. A machine learning analysis has been developed in order to discriminate signal from background. The algorithm has been trained using events acquired during antiproton extractions to the detector and background events recorded in beam-off periods. Recent measurements [4] will be discussed in the light of this data-driven analysis.

References

Testing CPT with the Anti-hydrogen Molecular Ion

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High precision radio-frequency, microwave and infra-red spectroscopic measurements of the anti-hydrogen molecular ion $\bar{H}_2^- (\bar{p}\bar{p}e^+)$, compared with its normal matter counterpart $H_2^+$, can provide direct tests of the CPT theorem. The fractional precision that can be achieved with such measurements can exceed that from comparing anti-protons with protons or anti-hydrogen with hydrogen. Schemes are outlined for measurements on a single $\bar{H}_2^-$ ion in a Penning trap, that use non-destructive state identification by measuring the cyclotron frequency and positron spin-flip frequency (using the continuous Stern-Gerlach technique), and also methods for creating an $\bar{H}_2^-$ ion and initializing its quantum state.
Toward an improved comparison of the proton-to-antiproton charge-to-mass ratio

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The BASE collaboration[1] conducts high-precision comparisons of the fundamental properties of the proton and the antiproton as stringent tests of CPT symmetry, such as a high-precision comparison of their charge-to-mass ratios. We performed such a measurement in 2014 [2], and currently aim to further improve the precision.

The principle of the measurement is to compare the cyclotron frequencies $\omega = qB/m$ of a single antiproton and a negative hydrogen ion $\text{H}^-$ in the same magnetic field $B$. The mass of the proton can be calculated from that of the $\text{H}^-$ with sub p.p.t. fractional accuracy, which enables us to compare $(q/m)_p$ and $(q/m)_\bar{p}$ with high precision.

In 2017, we commissioned an apparatus dedicated to such a measurement. The cyclotron frequency stability in the apparatus has been improved by a new magnetic shielding system and optimization of various environmental conditions to a point where we finally reached a stability better than in 2014 by a factor $> 2$.

In this presentation, different aspects of optimization procedures performed during CERN’s 2017 AD run will be summarized.

References


Electric dipole moment of light nuclei

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The measurement of the electric dipole moment (EDM) is an excellent test of the standard model of particle physics, and the detection of a finite value is signal of a new source of CP violation beyond it. In this talk, we review the EDM of light nuclei in the theoretical point-of-view. We discuss the enhancement and the suppression of the EDM of light nuclei which strongly depend on the nuclear structure [1].

References

Talks

Thursday $15^{th}$
Low-energy antiproton scattering

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The two-centre convergent close-coupling (CCC) approach is a general-purpose formalism applicable to a wide range of atomic collision processes. It was originally developed for positron scattering on atomic hydrogen including positronium (Ps) formation, see [1] and references therein. The CCC approach combines the expansion of the total wave function over the atomic states with that over the Ps states. Such a double expansion allows for explicit Ps formation, and allows for the distinction within the ionisation processes between Ps-formation and breakup channels. The approach is based on discretisation of the continuum and provides the complete solution to the three-body problem.

The quantum-mechanical CCC method was applied to study antihydrogen formation in the reaction \(\text{Ps}(n_i, l_i) + \bar{p} \rightarrow \bar{H}(n', l') + e^-\) at low energies [2]. We found increases of several orders of magnitude in \(\sigma_{\bar{H}}\) when \(n_i\) was raised from 1 to 2 and 3, with the cross sections for the excited states displaying a characteristic \(1/E\) dependence at low Ps kinetic energies \(E\). Recently we have extended the previous studies by considering Ps principal quantum numbers up to \(n_i = 5\) [3]. We have established that the dramatic increase in \(\sigma_{\bar{H}}\) when \(n_i\) is increased from 2 to 3 and from 1 to 2, was absent for the higher values of \(n_i\). In the Ps kinetic energy region where the data for all \(n_i\) behave as \(1/E\), there is only a factor of around 3 between the \(\sigma_{\bar{H}}\) for \(n_i = 5\) when compared to \(n_i = 3\). This is to be contrasted with the approximately factor of 30 increase between \(n_i = 2\) and 3, and a several orders of magnitude enhancement in the formation of \(\bar{H}\) via \(\bar{p}\) scattering with Ps in an \(n_i = 2\) excited state over the ground state [2]. It has been concluded that quantum effects dramatically suppress the increase of \(\sigma_{\bar{H}}\) in sharp contrast to expectations from Bohr-like and classical theories. If the trend in \(\sigma_{\bar{H}}\) persists at high \(n_i\), then the implications for current experimental efforts, which aim to exploit efficient charge transfer from excited-state Ps to produce \(\bar{H}\), could be severe.

The CCC approach has also been generalised to heavy particle collisions and applied to study low-energy \(\bar{p}\) scattering on atomic and molecular targets, see [4] and references therein. The continuous spectrum of the target is discretised using stationary wave packets constructed from the Coulomb wave function. The approach has been applied to calculate cross sections for \(\bar{p}\) collisions with various targets and excellent agreement with experiment has been observed where data are available [5]. A comprehensive set of benchmark results from integrated to fully differential cross sections for \(\bar{p}\) -impact ionisation in the energy range from 1 keV to 1 MeV has been obtained.

References

Ab-initio calculations of reactions involving the 3-body system \((\bar{p}, e^+, e^-)\) between the \(e^- + \tilde{H}(n = 2)\) and \(e^- + \tilde{H}(n = 3)\) thresholds

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Recently, we have developed a new method to solve Faddeev-Merkuriev equations using Lagrange-mesh techniques to describe collisions of the Coulombic three-body systems. This method has been applied to study \((\bar{p}, e^+, e^-)\) system in the energy range between the \(e^- + \tilde{H}(n = 2)\) and \(e^- + \tilde{H}(n = 3)\) thresholds [1]. Here, \(\bar{p}\) stands for antiproton, \(e^+\) for positron, \(e^-\) for electron, and \(\tilde{H}\) for antihydrogen. A special emphasis is made on the first charge exchange reaction of GBAR, \(\bar{p} + Ps \rightarrow e^- + \tilde{H}\) where \(Ps\) stands for the positronium. But our results can also be of interest for future experiments on antimatter (AEGIS, ...). One of the biggest challenges faced by GBAR is to find the best experimental and physical conditions (\(Ps\) state, antiproton energy etc...) to enhance the antihydrogen production. In this context, a special focus is made on the role played by Feshbach resonances and Gailitis-Damburg oscillations appearing in the vicinity of the \(\bar{p} + Ps(n = 2)\) threshold.

Our calculation show the existence of two Feshbach resonances, the first in the \(S\)-partial wave and the second in the \(P\) partial wave. In \(\bar{p} + Ps(n = 2) \rightarrow e^- + \tilde{H}(n = 2)\) scattering cross sections we have been able to highlight 4 Gailitis-Damburg oscillations, two in the \(S\) partial wave and, for the first time, two in the \(D\) partial wave. We have also found, for the first time, a Gailitis-Damburg oscillation in the \(P\)-wave partial cross section of antihydrogen excitation \(e^- + \tilde{H}(n = 1) \rightarrow e^- + \tilde{H}(n = 2)\). In addition to the new oscillations observed, our results are in very good agreement with previous works while giving more detailed cross sections [2,3].

References

Four-body treatment of the antihydrogen-positronium system: binding, structure, resonant states and collisions.

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We present the study of the binding, resonant and collisional properties of the $\bar{H} - Ps$ system. The binding energy, the life-times of the resonant states and the collisional cross sections are calculated and discussed.

To describe the structure of the $\bar{H} - Ps$ system we apply the variational approach based on the Gaussian Expansion Method (GEM). The variational manifold explicitly contains components of various arrangement channels expressed in terms of corresponding Jacobi coordinates. The use of Jacobi coordinates allows an efficient and rigorous treatment of the scattering cross sections.

The binding energy is calculated and discussed in terms of the contributions from various arrangement channels. Channel analysis helps to converge the binding energy and throws light on the structure and collisional properties of the system. The structure of the system is presented in terms of the correlation functions that portray the spatial distribution of the particles. This helps to understand the structure and dynamics of the system, in particular the change of the $\bar{H}^+$ upon binding of an electron, and the coexistence of the atomic and molecular features of $\bar{H}Ps$.

The resonant states and their life-times are calculated variationally using GEM in conjunction with the Complex Coordinate Method (CCM). The energies and widths of the resonances are analysed with respect to the channel composition of the resonant wave functions.

Based on the variational description of the four-body system, we apply the coupled rearrangement channels method to calculate the cross sections for $\bar{H} - Ps$ collisions. The outer part of the total wave function is made to satisfy the appropriate scattering boundary conditions for the collisional fragments. This is facilitated by the use of Jacobi coordinates in the description of the multi-channel structure of the wave function, that expressly contains various arrangement channels. The scattering matrix $S$ and the cross sections are obtained from the coupled, non-local integro-differential equations that explicitly couple the collisional channels of interest.
Production of light (anti-)(hyper-)nuclei in heavy-ion collisions

Silvia Masciocchi

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Collisions of heavy ions (such as Pb and Au) at ultra-relativistic energies provide excellent conditions to study the production of light nuclei and anti-nuclei, namely deuteron, triton, $^3$He, $^4$He and the lightest hyper-nucleus $^3\Lambda$H, to date. The production rate and the kinematic properties of the light nuclei are measured, together with some of their fundamental properties such as the mass-to-charge ratio difference between matter and anti-matter and the lifetime of the hyper-triton.

The abundance of the light nuclei created allows the investigation of their production mechanism. The nuclei production is described via two main approaches, either by the statistical thermal model or within the coalescence scenario. Very interesting insights are also provided by measurements of nuclei production in proton-proton and proton-ion collisions, as a function of the multiplicity of produced charged particles. Important information about the process of formation of nuclei can be acquired.

Recent results from ALICE at the LHC, CERN, Geneva, and by STAR at RHIC, Brookhaven National Laboratory, Upton, will be presented. Both experiments profit from excellent detectors for particle identification and high resolution track reconstruction. The figure below shows the specific energy loss of positively charged particles measured by the Time Projection Chamber of the ALICE experiment: the light nuclei can be clearly distinguished from the very abundant light hadrons. Experimental measurements will be presented and their comparison with model calculations will be discussed. High statistics measurements in the near future will make possible a significant progress in the field.

Figure 1: Specific energy loss of positively charged particles from Pb-Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV, as a function of the particle rigidity, measured by the ALICE Time Projection Chamber (the ALICE Collaboration).
Guiding and manipulating Rydberg positronium using inhomogeneous electric fields

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The short ground-state lifetime of Positronium (Ps) makes it challenging to perform precision-spectroscopy studies that require long interaction times. However, when excited to Rydberg states the annihilation rate of Ps becomes negligible [1], and the lifetime is dominated by fluorescence to low lying states. In addition, Rydberg Stark states with large Stark energy shifts have significant electric dipole moments which provide a mechanism by which forces can be applied to Ps atoms using inhomogeneous electric fields[2].

In a recent series of experiments we selectively excited individual Stark-states of Ps [3], guided the atoms using inhomogeneous electric fields in an atomic guide [4], and modified the guide to select a portion of the velocity distribution of the atoms with kinetic energies of $\sim 45$ meV [5]. Having a beam of slow Rydberg Ps atoms will lead to a number of applications including trapping Ps, measuring the Rydberg constant in a purely leptonic system [6], scattering and merged beams experiments, and potential antimatter gravity measurements.

Figure 1: (Left) Trajectory simulation for Ps in the ground state (a), $n = 10$ (b) and guided $n = 10$ with inhomogeneous electric fields. (Center) Experimental setup and detector position. (Right) Measured and calculated fluorescence lifetimes of Rydberg states ranging $n = 10$ to 19.

References
Tests of discrete symmetries in positronium decays
with the J-PET detector

P. Moskal on behalf of the J-PET collaboration

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Positronium is the lightest purely leptonic object decaying into photons. As an atom bound by a central potential, it is a parity eigenstate, and as an atom built out of an electron and an anti-electron, it is an eigenstate of the charge conjugation operator. Therefore, the positronium is a unique laboratory to study discrete symmetries whose precision is only limited, in principle, by the effects due to the weak interactions expected at the level of $10^{-14}$ [1] and photon-photon interactions expected at the level of $10^{-9}$ [2]. Violation of T or CP invariance in purely leptonic systems has never been seen thus far [3].

The experimental limits on CP and CPT symmetry violation in the decays of positronium are set at the level of $10^{-3}$ [4,5]. Thus, there is still a range of six order of magnitude where the phenomena beyond the Standard Model can be sought for by improving the experimental precision in investigations of decays of positronium atoms.

The newly constructed Jagiellonian Positron Emission Tomograph (J-PET) is the first PET tomograph built from plastic scintillators [6-11]. As a detector optimised for the registration of photons from the electron-positron annihilations, it also allows to perform tests of discrete symmetries in decays of positronium atoms via the determination of the expectation values of the discrete-symmetries-odd operators, which may be constructed from the spin of ortho-positronium atom and the momenta and polarization vectors of photons originating from its annihilation [12,13,14]. In the talk we will present the capability of the J-PET detector to improve the current precision of testing CP, T and CPT symmetries in the decays of positronium atoms and report on the first data-taking campaigns. With respect to the previous experiments performed with crystal-based detectors, J-PET built of plastic scintillators, provides superior time resolution, higher granularity, lower pile-ups, and opportunity to determine photon’s polarization through the registration of primary and secondary Compton scatterings in the detector. These features makes J-PET capable of improving present experimental limits in tests of discrete symmetries in decays of positronium atom (a purely leptonic system).

References

Recent progress in positronium experiments for Bose-Einstein condensation

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Positronium (Ps), the bound state of an electron and its antiparticle positron, is the lightest and most exotic hydrogen-like atom. Ortho-Ps is one of the best candidates for the first Bose-Einstein condensation (BEC) of any system which contains antimatter. Ps-BEC can be used to measure antimatter gravity using an atomic interferometer. It can also be used as a source for a 511 keV gamma-ray laser. Our target temperature and density to realize Ps-BEC is $\sim 10 K$ at $\sim 10^{17} cm^{-3}$. We proposed a new cooling scheme which is a combination of Ps thermalization and laser cooling \cite{1,2}. A schematic view of the proposed experimental setup is shown in Fig. 1. The recent results and prospects of our experiments to realize Ps-BEC will be presented.

![Conceptual view of the experimental setup. Positron bunches from a positron accumulator are injected into a cold silica cavity. Ps formed in the cavity is cooled by thermalization and 243 nm lasers.](image)

References

Observation of the hyperfine spectrum of antihydrogen

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Hyperfine spectroscopy of antihydrogen is one of the primary goals of the ALPHA experiment. Hydrogen’s zero-field ground-state hyperfine splitting frequency has been measured to better than 1 part in $10^{12}$ [1]. If we can reach a similar precision in antihydrogen it would provide an extremely precise test of CPT symmetry. An initial proof-of-principle experiment in 2012 demonstrated our ability to excite positron spin resonance transitions in trapped ground state antihydrogen [2]. Recently, ALPHA performed an improved microwave spectroscopy experiment in which the response of antihydrogen atoms was probed over a much finer range of frequencies [3]. This experiment was able to measure the two positron spin flip transitions at the same magnetic field and determine the hyperfine splitting in antihydrogen to be $1420.4 \pm 0.5$ MHz. I will present a detailed summary of that experiment and the tools we have developed to study antihydrogen’s hyperfine structure. I will also discuss recent improvements and the current status of ALPHA’s hyperfine spectroscopy experiments.

References

Spectroscopy of the $1S - 2P$ transition of antihydrogen

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While the hyperfine [1] and $1S - 2S$ transitions [2] in antihydrogen have been recently observed by the ALPHA collaboration, the $1S - 2P$ Lyman-alpha transition has a unique role to play. It will permit laser cooling of antihydrogen [3] to provide a cold and dense sample of antihydrogen for precision spectroscopy and gravity measurements. Challenges with the Lyman-alpha spectroscopy at 121.6 nm include the lack of convenient laser sources and optical components at these extremely short wavelengths. In order to detect the $1S - 2P$ transition of trapped antihydrogen, we have developed an all solid state nano-second pulsed laser system at 121.6 nm. We will discuss details of the 121.6 nm laser system at CERN and will report the status of the Lyman-alpha spectroscopy experiments with ALPHA.

References

Study of time reversal symmetry in the decay of Ortho-Positronium atoms using J-PET

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On Behalf of the J-PET Collaboration

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The Jagiellonian Positron Emission Tomograph (J-PET) is one of its kind based on organic scintillators being developed at Jagiellonian University in Krakow \cite{1}. J-PET is an axially symmetric and high acceptance scanner that can be used as a multi-purpose detector system. It is well suited to pursue tests of discrete symmetries in decays of positronium in addition to medical imaging. Positronium is a bound state of an electron and an anti-electron, and thus it is a purely leptonic object. This makes it ideal for the studies of discrete symmetries in the leptonic sector \cite{7}. The gamma quanta originating from positronium decay interact in the plastic scintillators predominantly via the Compton effect \cite{3}\cite{8}. Decays of ortho-positronium atoms into three photons can be reconstructed in terms of time and spatial coordinates of the decay using the trilateration-based method \cite{2}\cite{3}. J-PET enables the measurement of the momentum vector $\vec{k}_i$ and the polarization vector $\vec{\epsilon}_j$ of photons \cite{7}. Measurement of polarization of high energy photons (511 keV) is a unique feature of the J-PET detector which allows the study of time reversal symmetry violation by determining the expectation values of the time reversal symmetry odd operator \cite{7},

$$(\vec{\epsilon}_j,\vec{k}_i), \text{for} j \neq i \quad (2)$$

So far, Time reversal symmetry violation have not been observed in purely leptonic systems. The best experimental upper limits for CP and CPT (C-Charge Conjugation, P-Parity and T-Time) symmetry violation in positronium decay is set to 0.3x10\textsuperscript{-3} \cite{4} \cite{5}. According to the standard model predictions, photon-photon interaction or weak interaction can mimic the symmetry violation in the order of 10\textsuperscript{-9} (photon-photon interaction) and 10\textsuperscript{-13} (weak interactions) respectively \cite{9-11}. There is about 6 orders of magnitude difference between the present experimental upper limit and the standard model predictions \cite{6}. J-PET group aims to improve the sensitivity for the tests of the time reversal symmetry with respect to the previous experiments in the leptonic sector.

References

\begin{itemize}
  \item [10] W. Bernreyther et. al., Z. Phys. C 41, 143 (1988)
\end{itemize}
The Extra Low Energy Antiproton ring (ELENA) will be a critical upgrade to the unique Antiproton Decelerator facility at CERN and is currently being commissioned. ELENA will significantly enhance the achievable beam quality and enable new experiments.

To fully exploit the discovery potential of this facility, advances are urgently required in numerical tools that can adequately model beam transport, life time and interaction, beam diagnostics tools and detectors to fully characterize the beam’s properties, as well as in novel experiments that exploit the enhanced beam quality that ELENA will provide. These three areas form the scientific work packages of the new pan-European research and training initiative AVA (Accelerators Validating Antimatter physics). The project has received around 4M of funding from the European Union and brings together universities, research centers and industry to train 15 Fellows through research in this area.

This contribution gives an overview of the AVA research programme across its three scientific work packages. It also shows the upcoming events which AVA will organise for the wider antimatter research community.
Talks

Friday 16\textsuperscript{th}
Recent $\text{BaBar}$ results on CP violation

Sandrine Emery-Schrenk 1 on behalf of the $\text{BaBar}$ collaboration

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This review talk covers recent results of the $\text{BaBar}$ experiment on CP violation in the quark sector. It includes the recent measurement, using $\text{BaBar}$ and Belle data, of $\cos(2\beta) = \cos(2\phi_1)$ in $B^0 \to D(\ast)\ell^0$ with $D \to K^0_S\pi^+\pi^-$ decays, using a combined time-dependent Dalitz plot analysis. The analyses use the data sets of the $\text{BaBar}$ and Belle experiments containing $471 \times 10^6$ and $772 \times 10^6$ $B\bar{B}$ pairs collected at the $\Upsilon(4S)$ resonance at the asymmetric-energy B factories PEP-II at SLAC and KEKB at KEK, respectively.
Single-photon laser spectroscopy of cold antiprotonic helium

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The Atomic Spectroscopy and Collisions Using Slow Antiprotons (ASACUSA) collaboration is carrying out precise laser spectroscopy experiments on antiprotonic helium (\(\bar{p}\)He\(^+\equiv \bar{p} + \text{He}^{2+} + e^-\)) atoms [1,2]. Employing buffer-gas cooling techniques in a cryogenic gas target, samples of atoms were cooled to temperature \(T = 1.5-1.7\) K, thereby reducing the Doppler width in the single-photon resonance lines [3]. By comparing the results with three-body quantum electrodynamics calculations, the antiproton-to-electron mass ratio was determined as \(M_{\bar{p}}/m_e = 1836.1526734(15)\). Further improvements in the experimental precision are currently being attempted.

References

Constraints for fundamental short-range forces from the neutron whispering gallery, and extention of this method to atoms and antiatoms

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Extra fundamental short-range interactions mediated by new bosons are predicted in many extensions of the Standard Model of particle physics. They are also predicted in theories with large extra spatial dimensions and theories involving the light dark matter hypothesis.

To search for such interactions at different characteristic distances, the experimentalists use many methods including measurements of gravitational interaction at short distances, the search for extra interactions on top of the van der Waals/Casimir-Polder interaction, the search for rare processes in neutrino detectors, precision measurements with atoms, molecules and neutrons. Comparison of the sensitivities of different experiments to extra short-range forces in the standard Yukawa parametrization is published, for example, in ref. \cite{Ref1}.

A competitive method of searching at characteristic distances of about 10 nm is the precision measurement of the neutron whispering gallery \cite{Ref2}. This phenomenon is analogous to the well-known phenomenon of the whispering gallery of electromagnetic waves of a broad frequency range, as well as the sound wave. However, a material wave, for example a neutron wave, provides an additional possibility due to the existence of a nonzero neutron mass: for a neutron, the energy values of the whispering-gallery quantum states depend on the mass of the neutron and the interactions of this mass with the surface. Moreover, the neutron in such quantum states is localized at a distance from the surface of the order of tens of nanometers. Even a tiny extra force between the neutron and the surface at such distances would lead to a measurable shift in the energy of whispering-gallery quantum states.

We present the results of experiments performed with cold neutrons and estimate their sensitivity to extra short-range forces. We affirm that this method can also be extended to experiments with atoms and antiatoms \cite{Ref3}. The sensitivity of atomic experiments may be even higher than thus providing a similar, or even higher than the sensitivity of neutron experiments. More details could be found in \cite{Ref4}.

References

\cite{Ref2} V.V. Nesvizhevsky et al, Nature Phys. \textbf{6}, 114 (2010).
Several ongoing experiments at CERN aim at testing the CPT theorem and the weak equivalence principle using antimatter, among them the AEGIS experiment. For the latter, antiprotons inside a Penning trap interacting with Rydberg positronium form antihydrogen, which will then be used for precision measurements. The achievable sensitivity of these measurements is determined by the antihydrogen temperature which, for this production scheme, is determined by the temperature of the antiprotons. Two schemes relying on the use of laser-cooled anionic molecules to sympathetically cool antiprotons confined in the same trapping potential are under investigation, one relying on La- ions, and one on C2- molecules. After a short overview of both approaches, the focus will be put on a test setup to produce cold ground state C2- molecules that is currently being commissioned. This setup will be presented, together with a theoretical study on the feasibility of several laser cooling schemes, including one using the AC-Stark shift.

Laser cooling of anions — which has so far never been achieved — would also enable the sympathetic cooling of any other negatively charged species, opening new opportunities in a variety of research areas.

References

Positronium and Muonium two photon laser spectroscopy

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Positronium and muonium, being purely leptonic, are very interesting systems to test bound state QED free of finite size effects and hadronic corrections [1]. They are also very sensitive probes to search for New Physics [2] and can be used to extract fundamental constants such as the muon mass and magnetic moment [3].

In this talk, we report the current status of the ongoing experiment at ETH Zurich [4] aiming to improve the accuracy on the 1S-2S transition frequency of positronium in order to cross check the latest QED calculations [5]. We will present some preliminary results including the technique we developed to correct for the second order Doppler shift, the main systematic uncertainty in this experiment.

We will show that with the recent advances in UV laser technology, our novel cryogenic muonium converters and the detection techniques we developed for positronium spectroscopy, a 1000-fold improvement in the determination of the same transition in muonium compared to the current results [6] will be possible using the LEM beamline at PSI. This will provide the best determination of the muon mass at the 1 ppt level. It can also be used to extract the muon g-2 from the ongoing experiment at Fermilab which have a projected accuracy of 0.1 ppm [7]. In fact at this level, the comparison with the theoretical value will be limited by the current knowledge of the muon magnetic moment or the muon mass. Moreover, by using the expected results of the ongoing hyperfine splitting measurement of muonium in Japan at JPARC [8], it will provide one of the most sensitive tests of bound-state Quantum Electrodynamics. It will also allow to determine the Rydberg constant free from nuclear and finite-size effects at a level of $10^{-12}$ which is interesting in light of the proton charge radius puzzle [9] and provide a new determination of the fine structure constant at a level of 1 ppb. This has to be compared with the electron g-2 experiment at Harvard (0.24 ppb) [10] and the Rubidium experiment at Laboratoire Kastler Brossel (0.62 ppb) [11].

References

Production of cold muonium for future atomic physics and gravity experiments

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We are investigating methods to create a novel muonium (Mu) source, based on $\mu^+ \rightarrow \text{Mu}$ conversion in superfluid helium (SFHe), which has the potential of providing high brightness Mu beams for next generation laser spectroscopy experiments. We are also investigating the feasibility of using such sources for measuring the gravitational interaction of Mu. The positive muon ($\mu^+$) which is dominating the Mu mass is not only an elementary antiparticle, but a second-generation lepton too. This makes a gravity experiment highly motivated [1], and complementary to gravitational studies of antihydrogen [2,3,4] and positronium [5].

State-of-the-art Mu sources (like silica aerogel, mesoporous SiO$_2$) emit Mu atoms with a large (thermal) energy distribution, and wide ($\sim \cos \theta$) angular distribution. Cooling of these porous samples below 100 K results in rapidly declining numbers of vacuum-emitted muonium due to decreased mobility, and atoms sticking to the pore walls [6].

Our proposed method relies on stopping $\mu^+$ in a thin layer of SFHe, and forming Mu by capturing an electron from the ionization trail. A fraction of the Mu diffuses to the SFHe surface within their lifetime, where emission into vacuum occurs. The velocity of the emitted Mu ($\sim 6 \text{ mm/\mu s}$) is given by their large chemical potential ($E/k_B \sim 270 \text{ K}$) in SFHe, while the low temperature of the liquid ($T < 0.3 \text{ K}$) determines their transverse momentum [7].

In this talk, methods and challenges to create such SFHe Mu sources, the present status of the experiment in PSI, and the feasibility of an antimatter gravity experiment will be discussed.

References

Posters

Tuesday 13\textsuperscript{th} and Thursday 15\textsuperscript{th}
High sensitivity search for Pauli-forbidden atomic transitions at the LNGS underground laboratory

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The Pauli Exclusion Principle (PEP) and its connection to the spin-statistics theorem in fermionic systems represent a cornerstone of physics. However, from theoretical considerations there are speculations about possible violations in the lepton sector, i.e. for neutrinos, which would have severe consequences for cosmology. There were numerous attempts to attack experimentally the validity of the Pauli Exclusion Principle which are based on different assumptions and experimental methods. We conducted a very successful experiment VIP [1] which improved the limit for violation avoiding the Greenberg-Messiah superselection rule. In the current experiment VIP2 [2,3] at the Gran Sasso Laboratory (LNGS-INFN) we are want to further improve the limit of the validity of PEP for leptons by searching PEP-forbidden electron transitions in a high-sensitivity experiment. First results show that we can expect to reach a limit in the range of $10^{-31}$. The underlying concept of the experiment, preliminary results and an outlook for the next stages of VIP2 will be given.

Figure 1: Inner part of the VIP2 apparatus with the copper foil, the X-ray detection system and part of the active shielding.

References

AD infrastructures and experimental areas
evolutions in the context of ELENA development

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With the ongoing installation of the ELENA machine in the CERN AD facility, the AD infrastructures
must be adapted to cope with another 20 years of exploitation of the facility with improved conditions
for most experiments.
The first stages of improvements have been completed up to 2017 and the next stages of evolutions will be
reviewed, detailing the enlargement of some existing experimental areas, installation of new experimental
areas, maximization of usage of AD ground floor space for physics and AD facility consolidation program.
Models of $n\bar{n}$ transition in medium

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Abstract

The basic problems of the models of $n\bar{n}$ transition in medium and nuclei are discussed. The lower limits on the free-space $n\bar{n}$ oscillation time obtained by means of various models are considered.
Proton and neutron electromagnetic form factor and charge radius in lattice QCD

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In this talk, we present the recent lattice QCD study of electromagnetic form factor in the low energy scale, \( Q^2 \approx 0.02 \text{ GeV}^2 \), using large box, \( L^3 > 8 \text{ fm}^3 \) in the physical point. We non-perturbatively compute the electromagnetic form factor (Sachs form factor, \( G_E(Q^2) \) and \( G_M(Q^2) \)) as \( Q^2 \)-dependence for neutron and proton, and perform the theoretical calculation of charge radius,

\[
\langle r_E^2 \rangle = -6 \frac{d}{dQ^2} G_E(Q^2) \bigg|_{Q^2=0},
\]

from the first principle of QCD. Our study is directly comparable with experimental measurement of charge radius, and which can provide the theoretical information for “charge radius puzzle”.

As a by-product, we also compute the axial and pseudo-scalar form factor as \( Q^2 \)-dependence on the same gauge ensemble. This is used to estimate the axial-charge radius in lattice QCD, and we then compare those results with experimental measurement.
Antihydrogen production using directly injected antiprotons with reduced energy spread in
ASACUSA

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9. Department of Physics, Tokyo University of Science, 162-8601 Tokyo, Japan

The ASACUSA collaboration is developing an apparatus and methods to measure the ground-state hyperfine splitting of antihydrogen using a spin-polarized atomic beam \cite{ref1}. Antihydrogen atoms are produced in a cusp magnetic field whose gradients focus or defocus their trajectories depending on their magnetic moment \cite{ref2}. We have succeeded in producing antihydrogen atoms in the cusp field \cite{ref3} and in detecting them in the magnetic-field-free region at 2.7 m downstream of the production region \cite{ref4}. Antiprotons were injected from the antiproton accumulator MUSASHI into a pre-loaded positron plasma in order to produce antihydrogen, which is called direct injection method. For realization of the spectroscopy, the antihydrogen beam should be cold and its intensity should be as high as possible. As one possibility of utilizing the direct injection method, the injection scheme of antiprotons had been improved to avoid heating of the positron plasma as discussed in \cite{ref5}. We report further improvement on the energy spread of antiprotons directly measured at the cusp trap and observation of a high antihydrogen production rate at the timing of the antiproton injection. Recent developments of other mixing schemes will also be discussed briefly.

References

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Charge exchange three-body reaction in the presence of a laser field

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In order to make a direct observation of the effect of gravitation on antimatter, the GBAR [1] experiment aims at measuring the influence of Earth’s gravity in the trajectory of antihydrogen atoms. The first step of the experiment involves two successive low energy collisions. Indeed, the antihydrogen ions will be produced in two steps. The first one is the charge exchange three-body reaction (1): $\bar{p} + Ps(n_p) \rightarrow \bar{H}(n_h) + e^-$ where $\bar{p}$ stands for antiproton, $Ps(n_p)$ for positronium (bound positron-electron pair) either in ground state ($n_p = 1$) or in an excited state ($n_p = 2$), $\bar{H}(n_h)$ for antihydrogen (which can be also produced in an excited state $n_h \neq 1$) and $e^-$ for electron. The second one is a more complex four-body reaction (2): $\bar{H}(n_h) + Ps(n_p) \rightarrow \bar{H}^+ + e^-$, in which the antihydrogen produced in the first reaction interacts with another positronium to create an antihydrogen ion.

In this contribution we explore the possibility to increase significantly the antihydrogen positive ion production rate by assisting the capture processes involved in the three-body reaction (1) using a laser field having standard specifications (other than that used to excite the positronium). By using a formalism adapted from [2-4], we present an extensive study of the influence of the laser parameters (laser field strength and photon energy) on the charge exchange cross-sections in the energy range of interest for the GBAR’s experiment. Under special conditions the antihydrogen atom formation cross sections may be enhanced by the presence of the laser field (cf. Figure 1).

![Figure 1: Cross section of the reaction $\bar{p} + Ps(1s) \rightarrow \bar{H}(n_h = 2) + e^-$ as a function of the antiproton energy. Solid line: laser off; Dashed line: laser on with an electric field strength of $10^7$ V.cm$^{-1}$ corresponding to $I = 7.2 \times 10^{11}$ W.cm$^{-2}$.](image)

References

Gravitational and matter-wave spectroscopy of atomic hydrogen at ultra-low energies

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We propose an experimental study of atomic hydrogen gas at ultra-low temperatures $T < 100 \mu$K when the thermal energy of atoms is comparable with the changes of their potential energy in the Earth gravity field. At these conditions we are going to implement a gravitational spectroscopy for studies of quantum properties of ultra-cold atomic hydrogen and its interactions with matter and gravity, similar to experiments with ultra-cold neutrons [1,2]. We are going to build a magnetic trap for cooling a large number of H atoms below 1 mK, possibly reaching conditions for Bose-Einstein Condensation [3]. We will release ultra-slow atoms from the trap onto the cold surface of superfluid helium. Owing to the weakest interaction potential such surface provides nearly perfect reflecting conditions for low-energy atoms. This will allow studies of quantum bounces and stationary gravitational states of H atoms in the potential well created by this surface and the field of Earth gravity. The methods and ideas of this project may be useful for making similar experiments with antihydrogen which are currently prepared in CERN.

References

Beam Emittance Studies of Electron Cooling in ELENA

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The Extra Low ENergy Antiproton storage ring (ELENA) will provide high quality beams for antimatter experiments, decelerating antiprotons to a kinetic energy of 100 keV. At such low energies, it is important to correctly evaluate the long term beam stability. To provide a consistent explanation of the different physical phenomena affecting the beam, tracking simulations have been performed and the results are presented in this contribution. These include electron cooling simulations in the presence of various scattering effects. The impact of several imperfections in the electron cooling process on the beam quality are also discussed. In addition, analytical approximations of the temporal variation of emittance under these conditions are compared with numerical simulation results.
Development of TOF detector in GBAR experiment

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GBAR (Gravitational Behavior of Antihydrogen at Rest) experiment aims to measure the free fall acceleration of anti-Hydrogen atom in the terrestrial gravitational field. As one of main detection system, Time-Of-Flight (TOF) detector has been prepared to measure free-fall time of anti-Hydrogen by detecting secondary particles from the annihilation of anti-Hydrogen. TOF is composed of 44 long plastic scintillation bars surrounding 4 side of free fall chamber. The TOF design is optimized to measure secondary particles from annihilation and to distinguish cosmic ray background from the signal. We achieve the time resolution better than 100ps enough to distinguish the annihilation signal at the top of free-fall chamber from the cosmic ray background. We present the design of TOF, the time and the spatial resolution measured by cosmic ray and the results of simulation study based on GEANT4.
Towards sympathetic cooling and manipulation of single (anti-)protons by atomic ions in a double-well Penning trap

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High-precision experiments using (anti-)protons in Penning traps are an excellent system to implement a precise test of CPT invariance with baryons (see e.g. [1,2]). The current experiments are based on image current detection and the continuous Stern-Gerlach effect, where particle cooling and detection are performed by means of tuned LC-circuits. Here we present an alternative approach to these experiments using quantum logic inspired cooling and readout techniques based on a proposal by Heinzen and Wineland [3,4], which will allow to overcome current technical limitations linked to the finite temperature of (anti-)protons as well as speeding up the spin state detection [5]. For this purpose, a single laser-cooled \(^9\)Be\(^+\) ion will be used for sympathetic cooling and detection of single (anti-)protons employing an advanced cryogenic Penning trap system with a double-well potential. This experimental concept is under development with protons at Hanover and will be implemented with antiprotons at CERN within the BASE collaboration [6]. In this contribution, the experimental setup will be presented showing the status of the project, focusing on the trap geometry and associated infrastructure, as well as the next steps towards a microtrap-based double well potential for increasing coupling and loading of protons. We acknowledge funding by ERC StG QLEDS and DFG through SFB CRC 1227 DQ-mat, project B06.

References

Positronium decay study with the J-PET detector

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Jagiellonian Positron Emission Tomography (J-PET) is a first PET tomograph built from plastic scintillators [1-4]. As a detector optimised for the registration of photons from the positron-electron annihilation it is also used for the studies of the decays of positronium atoms [5-7].

In this poster we will present: (i) results of the commissioning of the J-PET detector, (ii) methods of the data selection and analysis, and (iii) first lifetime spectra of positronium (produced in the porous polymer [8]) measured with the J-PET detector.

References

Detection of charged particle, non neutral plasma, antihydrogen and positronium in \textit{AEgIS}

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(on behalf of the \textit{AEgIS} Collaboration)

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The main scientific goal of the \textit{AEgIS} experiment \cite{drobychev2007} is the direct measurement of the Earth’s local gravitational acceleration \(g\) on antihydrogen (\(\bar{H}\)). The weak equivalence principle is a foundation of General Relativity. It has been extensively tested with ordinary matter but very little is known about the gravitational interaction between matter and antimatter. Antihydrogen is to be produced in \textit{AEgIS} via charge exchange reactions between Rydberg-excited positronium and cooled down antiprotons \cite{doser2012}. Several detection techniques are extensively used to monitor antiproton and positron manipulations towards the antihydrogen formation inside the main apparatus. Positronium detection techniques underwent important improvements in sensitivity during last year and the detector dedicated to antihydrogen detection underwent upgrades and in-depth commissioning. An improvement of the antihydrogen detection efficiency is provided by incorporation of external scintillators into the expanded detection scheme, developed, tested and set up for the next data taking period.

References

\cite{drobychev2007, doser2012}
ON THE POSSIBILITY OF FORMATION OF EXOTIC PARTICLES AT THE CHANNELING OF LOW ENERGY ANTIPROTONS IN LiH CRYSTAL

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As an alternative to the traditional methods of exotic particles creation (see, for example [1]) in [2] it was proposed for the first time to generate protonium atoms p¯ p by proton capture in a LiH crystal by channeling of low energy antiprotons using nonstationary perturbation theory. In this paper, the possibility of generation of exotic protonium atoms p¯ p (as well as antiprotonic lithium ions ¯ pLi⁺) in the same crystal is proposed to be considered within the framework of the theory of sudden perturbations. Based on the quantum states ψ′±(r’) = (2πu±2)−3/4 exp(−r’2/4u±2) of Li⁺ and H⁻ ions, where u± are the amplitudes of their thermal oscillations, the amplitudes of the probabilities A±(ρ,n) = ∫ ψ′±(r’)ψn00(|r’−r|)exp(−iM±v(r’·e_z)/ℏ)dr’ (here M± are the masses of Li⁺ and H⁻ nuclei, v is antiproton velocity) of Li⁺ ions and protons capture into the quantum state ψn00(r) [3] of the antiproton are calculated (instead of the Bohr radius a₀ we take a₀/918). After averaging over the transverse coordinate ρ of the antiproton, channeled at zero angle relative to [110] axis of the LiH crystal, the probabilities W±(v) of the appearance of antiprotonic lithium ions ¯ pLi⁺ and protonium atoms p¯ p are calculated. Plots of functions ζ±(v) = W±(v)/W±(0), for example, for n = 1 (dashed curve) and n = 5 (solid curve) are shown in the figures below.

Figure 1: Plots of the probabilities of the appearance (in relative units) of exotic particles ¯ pLi⁺ - (a) and p¯ p - (b) at the channeling of low energy antiprotons in LiH crystal.

It is clear from this consideration that the probability of the appearance of antiprotonic lithium ions is about an order of magnitude higher than that of protonium atoms, but this occurs at lower velocities. We also note that the resonance character of dependences ζ±(v) does not change significantly with increase of n, but lead to decrease of the probabilities decrease.

References

DESCRIPTION OF THE TRANSMUTATION OF ELEMENTARY PARTICLES USING THE THEORY OF KNOTS

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It is known that the theory of knots has already been applied in physics for a long-time (see, for example, [1]). In the work [2] four families of fermions with the right and the left trefoils oriented are associated. In this paper electrons and positrons also are associated with the knots of right \((K_-)\) and left \((K_+)\) trefoils (see the Figure 1), for which the Jones polynomials are respectively equal \(V(K_-) = q + q^3 - q^4\) and \(V(K_+) = q^{-1} + q^{-3} - q^{-4}\) [1].

Figure 1: Image of the knots of the right \((K_-)\) and the left \((K_+)\) trefoils.

In [2] knots for four massless vector bosons, which in different combinations are connected sums of links \(K_-\) and \(K_+\) are also proposed. For example, a vector \(W^-\) boson can be associated with a knot \(K_W^- = K_- \sharp K_-\), for which the Jones polynomial in accordance with theorem in [3], is equal \(V(K_W^-) = V^2(K_-)\). Further, in this paper it is emphasized that using theory of knots it is possible to describe the decay processes of elementary particles if we use the property of Jones polynomials for the disconnected sum of knots, namely \(V(K_1 \sqcup K_2) = -V(K_1)V(K_2)(q^{1/2} + q^{-1/2})\) [3]. Applying this property to one of the decay channels \(W^- \to e^- + e^- + \bar{\nu}_e\) (see, for example, [4]), we find the Jones polynomial \(V(K_{\bar{\nu}_e}) = (q^{1/2} + q^{-1/2})^{-2}\) for the electron antineutrino \(\bar{\nu}_e\). It is obvious that an analysis based on the theory of knots can also be applied to many other transmutations of elementary particles.

In conclusion, we note that this mathematical description of elementary particles by means of knots (knotted strings) can also give some physical interpretation. As it is stated in [5], two vacuums can be constructed from right and left trefoils, namely a vacuum of dark matter with Planck energy density and a physical vacuum of the surrounding space with zero energy density. If such consideration is correct, than we can assume that at Planck distances there should exist energy flows with the topology of open and knotted strings, which are compared with elementary particles.

References

Realistic 3D implementation of electrostatic elements for low energy machines

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Novel antimatter experiments at CERN require high intensity, low energy (<100 keV) antiproton beams. Each experiment has a set of desirable beam parameters. To achieve this, and obtain the greatest efficiency, transfer lines will be based on electrostatic optics. Unfortunately, only a small amount of simulation codes allow realistic and flexible implementation of such elements.

In this contribution, methods for accurately creating and tracking through electrostatic optical elements are presented, utilising a combination of a modified version of G4Beamline [1] and finite element methods. To validate our approaches the transfer line from the ELENA ring to the ALPHA experiment was chosen as a basis for particle tracking studies. A range of approaches to modelling the electrostatic elements were explored, ranging from simple field expressions, to the complex field maps used in the final model. An investigation into the achievable beam quality at ALPHA is presented.

References

High intensity positron beam production for the GBAR experiment

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The main goal of the GBAR (Gravitational Behaviour of Antihydrogen at Rest) experiment is to test the weak equivalence principle for antimatter using $\bar{H}$ [1]. In order to perform that complex experiment, ultracold antihydrogen atoms ($\approx 10\mu K$) are needed. As it is impossible to cool down neutrals to required temperature, GBAR will produce the antihydrogen ion and measure its free fall time after detachment of an extra positron.

The antihydrogen ion production for the GBAR collaboration is made through the charge exchange reactions with positronium $Ps$, $\bar{p} + Ps^* \rightarrow \bar{H}^* + e^-$ and $\bar{H}^* + Ps^* \rightarrow \bar{H}^+ + e^-$. The main ingredient for those reactions is a high density positronium cloud, which can be produced by implanting high intensity positron beam into porous silica target.

The GBAR team designed a positron source based on a 9 MeV electron linac. The final linac structure is currently being commissioned and will reach 300 mA peak current with 300 Hz repetition rate. In this poster the scheme of the positron production line and the newest results will be presented.

References

Sympathetic cooling of $\bar{\text{H}}^+$

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One important step in the GBAR project is sympathetic cooling of the $\bar{\text{H}}^+$ ion by laser cooled Be$^+$ ions from eV energies down to µeV (thousands of K down to mK). We follow several approaches to tackle this issue.

The first one relies on numerical simulations taking into account the RF trapping field of the Paul trap and the exact coulomb interactions between the ions. It shows that an mixed specie ion cloud containing containing Be$^+$ and HD$^+$ is much more efficient than a pure Be$^+$ ion cloud because mechanical couplings are much better with a mass ratio of three rather than with a mass ratio of 9.

The second approach is experimental and uses on a Sr$^+/\text{Be}^+$ mixed ion cloud having a comparable 86/9 mass ratio. Both ion species can be imaged on a CCD camera, which allow for monitoring the sympathetic cooling dynamics of the light ion (Be$^+$) by the heavy one (Sr$^+$).

The $\bar{\text{H}}^+$ ion can be easily photodetached by the Be$^+$ cooling light at 313 nm. We show that laser cooling to low temperature and Coulomb crystallisation are also effective with a donought (Laguerre-Gauss) mode.

3D-imaging of antimatter annihilation using the ASACUSA Micromegas tracker

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The ASACUSA collaboration aims at measuring the ground state hyperfine splitting of antihydrogen for probing fundamental symmetries. A cryogenic double cusp trap for mixing antiprotons and positrons serves as an antihydrogen source for inflight spectroscopy \cite{1,2}. In order to be able to monitor the antihydrogen formation process, the ASACUSA Micromegas Tracking (AMT) detector was installed for detecting and reconstructing the antiproton and antihydrogen annihilations in the trap in three dimensions \cite{3}.

The AMT detector consists out of two curved gaseous detector layers using micromegas technology \cite{4}. The layers form two half cylinders and are mounted concentrically with the trap electrodes on the upper side of the vacuum chamber containing the trap. A single, full-cylinder layer of plastic scintillator between the two Micromegas layers provides fast signals for triggering the read out of the micromegas channels. As an active gas, a mixture of argon (90\%) and isobutane (10\%) is used. The drift region has a height of 3\,mm, while the amplification region has a height of 128\,µm. A relatively high drift voltage of 1600 V and an amplification potential of 460 V are applied, which sufficiently reduce the influence of the Lorentz force on the drift electrons due to the magnetic field of the trap.

Besides explaining the AMT detector in detail and describing the event reconstruction algorithm, we present annihilation data recorded during the 2016 beam time. Annihilation data from antiprotons show that the AMT detector is able to discriminate between annihilations on-axis and on the inner electrode walls of the trap \cite{5}. The latter type of events are the primary signal candidates to be antihydrogen atoms.

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Casimir-Polder shifts on quantum levitation states

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An ultracold atom above a horizontal mirror experiences quantum reflection from the attractive Casimir-Polder interaction, which holds it against gravity and leads to quantum levitation states. We analyze this system by using a Liouville transformation of the Schrödinger equation and a Langer coordinate adapted to problems with a classical turning point. Reflection on the Casimir-Polder attractive well is replaced by reflection on a repulsive wall and the problem is then viewed as an ultracold atom trapped inside a cavity with gravity and Casimir-Polder potentials acting respectively as top and bottom mirrors. We calculate numerically Casimir-Polder shifts of the energies of the cavity resonances and propose a new approximate treatment which is precise enough to discuss spectroscopy experiments aiming at tests of the weak equivalence principle on antihydrogen. We also discuss the lifetimes by calculating complex energies associated with cavity resonances.

Figure 1: Potential landscape for antihydrogen atom in the combined gravity and CP potentials, before (on the left) and after (on the right) a Liouville transformation. Color lines represent the energy levels.
Intensity measurement of the Antiproton Decelerator beam using a Cryogenic Current Comparator with nano-ampere resolution

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The Antiproton Decelerator (AD) and Extra Low ENergy Antiproton (ELENA) rings at CERN decelerate beams containing $10^7$ antiprotons. These low-intensity particle beams are particularly challenging for non-perturbative beam diagnostics due to the small amplitude of the induced electromagnetic fields. However, an absolute intensity measurement of the circulating beam is essential to monitor the operational efficiency, reduce beam commissioning times and to provide important calibration data for the antimatter experiments. This paper reviews the design of an operational Cryogenic Current Comparator (CCC) based on Superconducting QUantum Interference Device (SQUID) for current and intensity monitoring in the AD. Such a system has been operational throughout 2017, relying on a stand-alone liquid helium cryostat with cooling power provided by a pulse-tube cryocooler. The performance of the intensity beam diagnostic and of the cryogenic system is also presented, confirming a resolution in the nano-ampere range, with both bunched and coasting beam.

References
Feasibility study of the measurement of annihilation photons polarization with the J-PET detector

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J-PET is a prototype of the positron emission tomograph built from plastic scintillators [1,2,3] in which photons interact predominantly via Compton effect. Thanks to Klein-Nishina formula polarization may be estimated by measurement of the direction of primary and scattered photons. Knowledge about polarization of photons originating from the decay of positronium allows us to study various physical phenomena such as quantum entanglement [4] and discrete symmetries breaking [5]. The poster will present results of simulations showing the possibilities of the J-PET detector for the polarisation determination of the 511 keV photons.

References

Simulations of the formation of trappable antihydrogen

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We simulate the formation of antihydrogen through three-body recombination when antiprotons are injected into a positron plasma, which is trapped in a Penning trap. Here, we focus on the fraction that fulfil the conditions necessary for confinement of anti-atoms in a magnetic minimum trap. Our method is based on classical trajectories of positrons and antiprotons, and has been explained in detail in [1]. Antihydrogen atoms formed inside a positron plasma are followed until they leave the plasma radially. At this point it is determined whether the antiatom could be magnetically trapped. For this to be the case it has to fulfil three conditions:

1. It has to be bound and stable. This is tested by simulating the influence of a 10 V/cm axial electric field for the duration of 1 µs. If the antiatom is still bound after this time, we classify it as a stable antihydrogen.

2. It has to be in a low-field seeking state. That is, its orbital angular momentum must be antiparallel to the magnetic field.

3. Its kinetic energy must be less than 2 Kelvin. This is larger than the depth of current magnetic traps, but was chosen to get sufficient statistics within a reasonable time. If one assumes that the initially formed antiatoms follow a thermal distribution with temperature $\gg$ 2 Kelvin, one can easily scale our results to lower trap depths.

In our simulations we have used the positron temperature, the positron density, and the trap radius where the antiprotons are injected as parameters. Trapping fractions of around $10^{-4}$ are found under conditions similar to those used in recent experiments, and in reasonable accord with their results. We find that collisional effects play a beneficial role via a redistribution of the antihydrogen magnetic moment, allowing enhancements of the yield of low-field seeking states that are amenable to trapping. We also find unexpected features in the distribution of binding energies.

References

Lifetime of Magnetically Trapped Antihydrogen in ALPHA

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How long antihydrogen atoms linger in the ALPHA magnetic trap is an important characteristics of the ALPHA apparatus. The initial trapping experiments in 2010 [1] were conducted with 38 detected antiatoms confined for 172 ms and in 2011 [2] with seven for 1000 s. Long confinement times are necessary to perform detailed frequency scans during spectroscopic measurements. An analysis carried out, using machine learning methods, on more than 1000 antiatoms confined for several hours in the ALPHA-2 magnetic trap, yields a preliminary lower limit to the lifetime of 66 hours. Hence this observation suggests that the measured confinement time of antihydrogen is extended by more than two orders of magnitude.

References

Magnetometry Techniques for Gravitational Measurements of Antihydrogen with ALPHA-g

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The ALPHA collaboration is constructing a new apparatus (ALPHA-g) to measure matter-antimatter gravitational interactions with magnetically trapped antihydrogen. The magnetic forces that are used for antiatom containment will dominate over the gravitational forces we hope to measure. In order to distinguish between these two types of forces experienced by the antihydrogen atoms, custom, high precision magnetometry methods need to be developed. This poster will discuss techniques borrowed from the fields of non-neutral plasmas and nuclear magnetic resonance. These methods are deployed in tandem and result in magnetic field sensors with precisions of about 1 part in 10,000. The implications of this precision on antihydrogen gravity measurements are considered. Factors limiting our magnetic field measurements are also discussed, as well as directions for improvement.
Development of the Radial Time Projection Chamber for the ALPHA-g antimatter gravity experiment

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Antimatter is believed to be affected by gravity in exactly the same way as ordinary matter for a variety of good reasons [1], however this has never been measured directly. This will be tested by the ALPHA-g project, which uses a new vertical antihydrogen trap based on the previous ALPHA design (Antihydrogen Laser Physics Apparatus, the first experiment to trap antihydrogen in 2010 [2]). As in previous ALPHA experiments, the trapped antihydrogen is detected via its charged annihilation products after switching off the trap. In order to be sensitive to small gravitational effects, the setup extends more than 2 metres in the vertical direction, requiring the particle detection system to cover a large volume with good tracking accuracy. The design chosen to replace the previous experiments’ silicon strip detectors is a radial time-projection-chamber (rTPC) filled with an Argon/CO₂ gas mixture.

Following successful tests with a smaller prototype, the full-scale chamber was completed in early 2018 and the basic functionality of the detector was established. Soon after, initial tests with cosmic rays lead to the observation of tracks due to charged particles.

The specific parameters of the chamber together with the necessity to observe minimum-ionizing particles leads to relatively complex signals on the detector electrodes, which have to be deconvolved in an iterative process. The deconvolution algorithm and its results for both simulated and prototype signals are presented.

References

The weight of antimatter is a crucial missing measurement in our picture of the natural world. It is important in two ways: (1) The predominance of matter created in the Big Bang demands some form of mismatch in properties between matter and antimatter. Many experiments have sensitively compared their charge, magnetic moment, nuclear bonding and decay behaviour, yet no significant mismatch has been found to date to explain the cosmic matter dominance. One of the last unexplored domains is gravitational behaviour. (2) Our understanding of the subatomic world is wholly incompatible with General Relativity, the dominant phenomenon on astronomical scales. New ideas on a unified theory on atomic and gravitational interactions may require antimatter to respond uniquely to gravity. Measuring such behaviour experimentally will provide vital evidence to accept or reject these ideas, and further the development of a unified view of nature.

Experimentally, weighing antimatter has been difficult because electrical influences on the charged, energetic antiparticles commonly created in accelerators massively overwhelm their gravitational response. Their short life in these machines also leaves no time for observation. The antihydrogen trapping technology developed by the world-leading ALPHA collaboration has, however, completely altered this picture, by generating antimatter that has low energy, long lifetime and immunity to electric forces. The new ALPHA-g experiment is designed to leverage this new technology, and weigh antimatter by letting antiatoms escape through the bottom and top of a tall magnetic confinement system. By precisely controlling the magnetic field of the openings, the escape bias induced by gravity can infer antihydrogen weight to within 1%. This constitutes the most sensitive antimatter gravity measurement ever made, and a significant breakthrough in subatomic and fundamental physics.

This poster presentation outlines the design of the magnetic confinement and measurement system of ALPHA-g, the challenges to achieving magnetic control necessary for a 1% precision in antihydrogen gravity, and the techniques developed to mitigate them.
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