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Book of Abstracts

Contents

Parallel I / 1

Design and characterisation of an antiproton deceleration beamline for the PUMA experiment

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We report on the design and characterization of an antiproton deceleration beamline, based on a pulsed drift tube, for the PUMA experiment at the Antimatter Factory at CERN. The design has been tailored to high-voltage (100 kV) and ultra-high vacuum (below 10^{-10} mbar) conditions. A first operation achieved decelerating antiprotons from an initial energy of 100 keV down to (3898 ± 3) eV, marking the initial stage in trapping antiprotons for the PUMA experiment. Employing a high-voltage ramping scheme, the pressure remains below 2×10^{-10} mbar upstream of the pulsed drift tube for 75% of the cycle time. The beamline reached a transmission of $(55 \pm 3)\%$ for antiprotons decelerated to 4keV. The beam is focused on a position sensitive detector to a spot with horizontal and vertical standard deviations of $\sigma_{\mathrm{horiz}} = (3.0 \pm 0.1)$ mm and $\sigma_{\mathrm{vert}} = (3.8 \pm 0.2)$ mm, respectively. This spot size is within the acceptance of the PUMA Penning trap.

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Positron Annihilation in the Universe

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One of the major tasks of astrophysics is to understand the emission mechanisms of observed sources and regions in the sky. Only by pinpointing down these mechanisms, it is possible to derive physical parameters and learn about the evolution of astrophysical objects. Alas, many observations of high-energy phenomena are ambiguous, requiring more and orthogonal information. The nature of several sources, among others accreting X-ray binary systems, core-collapse and thermonuclear supernovae, cosmic-rays, stellar flares and potentially dark matter, all show signatures of positron production and annihilation. Utilising this underrated emission mechanism can shed light on unsolved problems in astrophysics and cosmology.
In this talk, I will show examples of how we can learn from these gamma-ray signatures already now with ESA's INTEGRAL observatory, and what might be possible in the context of new gamma-ray satellite missions, such as the accepted NASA mission COSI.

Poster / 4

The Lepton Symmetry Experiment: LSym

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One of the prevailing enigmas in contemporary physics is the observed disparity between the abundance of matter and antimatter in the universe, posing a fundamental challenge to the principles of the Standard Model of particle physics.

Within the LSym experiment we plan to compare the fundamental properties, specifically the charge-to-mass ratios and the g-factors, of the electron and the positron in a cryogenic Penning trap to 14 digits precision and thereby performing a highly sensitive test of matter-antimatter symmetry in the lepton sector [1]. This precision can be achieved by simultaneously trapping both the particles in the same trap. Once the positron is cooled to the ground state of motion in a millikelvin-cooled Penning trap that forms a custom-tailored millimeter-wave cavity, we can measure the coherent difference of the spin precession frequencies of the matter and antimatter particles [2].

In the contribution, the experimental setup, techniques and challenges will be presented.

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Parallel I / 7

The LSym experiment: a CPT symmetry test in the leptonic sector

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The LSym experiment is a new cryogenic Penning trap experiment currently being designed at the Max-Planck-Institut für Kernphysik of Heidelberg. The goal of LSym is to conduct a stringent CPT test by comparing the properties of matter and antimatter with unprecedented sensitivity by trapping simultaneously one electron and one positron in a Penning trap, which allows performing a *decoherence-free* measurement. This project will present a few challenges, for instance the optimisation of positron production and accumulation, given a rather weak radioactive ^{22}Na source (about 15 MBq).
The positrons from the β^+ decay of ^{22}Na have to be moderated to become trappable. Here, following [1], we utilize a tungsten foil to produce positronium in a high Rydberg state, which can be field-ionised inside the Penning trap. The trapped positrons are then cooled to the motional ground state in a deep-cryogenic microwave cavity trap operated at about 300mK. This presentation illustrates the principles and techniques that will be used at LSym.

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Parallel I / 8

Towards a transportable antiproton reservoir

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The world's only source of low-energy antiprotons is currently the AD/ELENA facility located at CERN. Precision measurements on single antiprotons have been conducted at this facility and provide stringent tests of fundamental interactions and their symmetries. However, magnetic field fluctuations from the facility operation limit the precision of upcoming measurements. To overcome this limitation, we have designed the transportable antiproton trap system BASE-STEP to relocate antiprotons to laboratories with a calm magnetic environment. We present the technical design, characterization measurements of the transportable superconducting magnet, and the current status of the transportable antiproton trap BASE-STEP.

Poster / 9

A new concept of Mu-atniMu conversion search

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The conversion from muonium (Mu, μ+e-) to anti-muonium (antiMu, μ-e+) is strongly suppressed in the Standard Model (SM) of particle physics because it violates the conservation of the leptonic family number. In many theories of SM extension, leptonic family numbers (lepton flavors) are not conserved and then the Mu-antiMu conversion can become observable level, just below the current experimental upper limit of 8.3×10^{-11}. Though the search for the Mu-antiMu conversion is strongly motivated in this way, a new experimental method is required to go beyond the current limit which is determined by beam-related background.

We propose to search for the Mu-antiMu conversion with a new method; Mu is produced by injecting muon into a muonium production target such as silica aerogel. Converted antiMu is ionized by laser

and μ- is transported by electric and magnetic components. Because there is no source of μ- in such an experimental setup, background-free search can be conducted. This method needs an intense pulsed muon beam and a laser system, both of which could be available in MLF J-PARC.
We will present the details of this new Mu-antiMu search concept and the result of the feasibility study performed in D line, MLF to confirm the background level is low enough.

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J-PARC - future plans, hadron hall

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The J-PARC Hadron Experimental Facility was constructed with an aim to explore the origin and evolution of matter in the universe through the experiments with intense particle beams. Over the past decade, many results in particle and nuclear physics have been obtained at the present facility. In order to expand the physics programs to unexplored regions that have never been reached, the extension project of the Hadron Experimental Facility has been extensively discussed. We will discuss the physics of the current and the extended Hadron Experimental Facility for solving the issues in the fields of the strangeness nuclear physics, hadron physics, and flavor physics.

Parallel I / 11

Cosmic $\overline{\mathrm{d}}$ and $\overline{\mathrm{He}}$: production mechanisms and latest constraints from ALICE at the LHC

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The formation mechanism of light (anti)nuclei in high-energy hadronic collisions remains an open question in high-energy physics. Their production mechanism is investigated by comparing experimental data with phenomenological models using statistical hadronization or a coalescence approach.

In particular, the coalescence mechanism finds an essential application in cosmic antinuclei studies for indirect dark matter searches with space-based experiments like AMS.
Cosmic $\overline{\mathrm{d}}$ and $\overline{\mathrm{He}}$ are supposed to be produced via coalescence of nucleons stemming from either dark matter particle interaction or decay, or by interactions of primary cosmic rays with the interstellar matter. Constraining the (anti)nuclei formation mechanism with experiments in controlled conditions at accelerators is essential to reduce uncertainties on cosmic antinuclei flux estimates.

Thanks to the excellent tracking and particle identification performance, the ALICE experiment has performed a broad set of precision measurements on (anti)nuclei produced in different collision systems (pp, p-Pb and Pb-Pb) since the beginning of its operations. Furthermore, the ALICE apparatus underwent a series of major upgrades to take full advantage of the luminosity increase of the LHC Run 3. The results of these latest Run 3 d ($\overline{\mathrm{d}}$) and $^{3}\mathrm{He}$ ($^{3}\overline{\mathrm{He}}$) measurements, the most recent results on the measured formation probability of bound objects as a function of the final-state charged particle multiplicity in comparison to state-of-the-art models, will be widely discussed.

Parallel I / 12

Development of a Pressurized Helium Scintillating Calorimeter for AntiMatter Identification.

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The search for low energy anti-nuclei in cosmic rays allows a test of fundamental physics problems such as the possible presence of primordial antimatter or the nature of Dark Matter.
The "PHeSCAMI"(Pressurized Helium Scintillating Calorimeter for AntiMatter Identification) project is aiming to study a new signature for the identification of anti-nuclei in cosmic rays.
In particular, anti-protons or anti-deuterons stopping in a medium can produce exotic atoms and for the particular case of an helium target, the captured antiparticle can orbit the nucleus for microseconds before the annihilation.
This characteristic delayed annihilation is a very distinctive signature able to identify the antimatter nature of the stopping particle and rejecting the ordinary matter cosmic rays.
A possible configuration for the "PHeSCAMI"detector consists of a pressurized helium scintillating calorimeter surrounded by plastic scintillator layers for velocity measurement.
Anti-deuterons are identified by combining the spectrometric measurement of the stopping particle (velocity vs energy) with the delayed emission of outgoing charged pions caused by the anti-nucleus annihilation.
A first prototype of the pressurized calorimeter, made by 1L stainless steel vessel filled by 200 Bar Helium acting as a scintillator, has been characterized with cosmic muons and with 70-240 MeV proton beam in the INFN-TIFPA laboratory. This allows us to prove an energy resolution better than 10% and a time resolution within 300ps for the scintillating helium calorimeters.
The development and test of an advanced calorimeter prototype, with a volume of 40L, pressure of 200 Bar and wall grammage within 1.5g/cmˆ2, based on an automotive COPV (composite overwrapped pressure vessel) is ongoing in the INFN-TIFPA laboratory.
The status of the PHeSCAMI project will be summarized and the results of the measured performance of the Helium calorimeter prototypes will be shown.

Parallel I / 13

High-Resolution Spectroscopy of Muonic Lithium - First Steps and Prospects of the QUARTET Experiment

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Precise measurements of absolute nuclear charge radii are crucial ingredients for QED tests and are valuable benchmarks for modern nuclear structure theory [1]. Muonic atom spectroscopy is well known as an ideal method to accurately determine the root-mean-square (RMS) radii of the nuclear charge density distribution. By measurements of the 2p-1s transitions of muonic atoms, this technique has already provided precise measurements for the very light (Z<3) as well as heavier nuclei (Z>10) [2]. However, a gap for muonic atoms from lithium to neon remains due to the inaccessibility of the relevant energy range (˜20-200 keV) via laser spectroscopy and the insufficient resolution of conventional solid-state detectors for precision measurements.
To address this gap, the QUARTET collaboration employs cryogenic metallic magnetic calorimeters (MMCs), which combine broad-band spectra with record resolving power, to perform spectroscopy of light muonic atoms and to refine the nuclear charge radii of light nuclei from lithium to neon [3]. In October 2023, QUARTET's first test beam time took place at the Paul Scherrer Institute (PSI), where the feasibility of this approach has been demonstrated successfully. This contribution presents the status and plans of the experiment and shows the first broad-band high-resolution spectra of muonic lithium obtained with an MMC.

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BASE –towards a 10-fold improved measurement of the antiproton magnetic moment

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BASE is a collaboration whose main experiment is located at CERN, with the goal of contributing to resolving the puzzle of the striking matter-antimatter imbalance and the mystery of the origin of dark matter. The related experiments are conducted by performing ultra-precise comparisons of the fundamental properties of single antiprotons and protons trapped in a sophisticated four Penning-trap system.

The flagship experiments uniquely conducted by the BASE collaboration are the magnetic moment measurements of single protons and antiprotons. Our last measurements, the most precise determinations of these constants to date, are at the 300 p.p.t. level for protons (G. Schneider, A. Mooser, S. Ulmer, et al. Science 358, 1081 (2017)) and at 1.5 p.p.b. for antiprotons (C. Smorra, S. Ulmer, et al. Nature 550, pages 371–374 (2017)). To improve these limits, we have developed many new technological innovations and experimental methods, including fast sub-thermal cooling, a superconducting magnetic field compensation system, a new antiproton catching system for the ELENA era, and an ultra-stable quantum spin-state detection system. Putting all these experimental developments together, we are currently conducting a new proton/antiproton magnetic moment measurement campaign, with the goal to improve the precision in the determination of the antiproton magnetic moment by a factor of 5 to 10.

In this talk, I will report on the status of the BASE experiment, focusing on the progress made towards more precise proton and antiproton magnetic moment measurements. I will discuss the current experimental limitations and plans for future improvements, that will be based on the first coherent single-particle nuclear spin-quantum-spectroscopy.

Poster / **15**

Towards laser cooling of negative molecular ions

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The AEgIS experiment at CERN's Antiproton Decelerator aims at measuring the gravitational acceleration $\bar{g}$ of antihydrogen ($\bar{H}$) with high precision [1, 2]. A key limitation in these measurements is the $\bar{H}$ temperature: The thermal motion of the $\bar{H}$ atoms blurs their free-fall trajectories and thus limits the achievable $\bar{g}$ precision.

The temperature of antihydrogen, which is formed at AEgIS in a laser-induced charge transfer reaction between positronium and antiprotons ($\bar{p}$), is dominated by the temperature of the antiproton precursors. With the current passive cooling scheme, the achievable $\bar{p}$ temperature is limited to at best tens (but to date a few hundred) kelvin.

Sympathetic cooling of antiprotons through thermalization with co-trapped laser-cooled ions would enable achieving temperatures in the mK range. However, to avoid annihilation, the co-trapped coolant ions must be negatively charged.

The Borealis project at AEgIS aims at realizing Doppler laser cooling of a negative ion. In particular, the diatomic molecular C_2^- ion, a well-suited anion species for laser cooling [3], has been produced, mass-selected and stored in a linear Paul trap [4]. Currently, the capture efficiency of the trap and the lifetime of trapped C_2^- ions are improved and preparations for preliminary in-beam spectroscopic studies are underway.

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Hypertriton lifetime

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Over the last decade, conflicting values of the hypertriton (${}^3_\Lambda\mathrm{H}$) lifetime ($\tau({}^3_\Lambda\mathrm{H})$) were extracted from relativistic heavy-ion (RHI) collision experiments, ranging from values compatible with the free-Λ lifetime (τ_Λ)-as expected naively for a very weakly bound Λ in ${}^3_\Lambda\mathrm{H}$-to lifetimes as short as $\tau({}^3_\Lambda\mathrm{H}) \approx (0.4–0.7)\tau_\Lambda$. A similarly large spread of values has been obtained also in earlier measurements.

Recently, we revisited theoretically this ${}^3_\Lambda\mathrm{H}$ lifetime puzzle, using ${}^3_\Lambda\mathrm{H}$ and ${}^3\mathrm{He}$ wave functions computed within the *ab initio* no-core shell model employing interactions derived from chiral effective field theory to calculate the two-body decay rate $\Gamma({}^3_\Lambda\mathrm{H} \to {}^3\mathrm{He} + \pi^-)$. To derive $\tau({}^3_\Lambda\mathrm{H})$, we evaluated the inclusive π^- decay rate $\Gamma_{\pi^-}({}^3_\Lambda\mathrm{H})$ by using the measured branching ratio $\Gamma({}^3_\Lambda\mathrm{H} \to {}^3\mathrm{He} + \pi^-)/\Gamma_{\pi^-}({}^3_\Lambda\mathrm{H})$ and added the π^0 contributions through the $\Delta I = \frac{1}{2}$ rule. We found significant but opposing contributions to $\tau({}^3_\Lambda\mathrm{H})$ arising from ΣNN admixtures in ${}^3_\Lambda\mathrm{H}$ and from $\pi^- - {}^3\mathrm{He}$ final-state interaction [1], as well as substantial theoretical uncertainties inherent in the employed nuclear and hypernuclear interaction models [2]. Since $\tau({}^3_\Lambda\mathrm{H})$ was found to be strongly correlated with the Λ separation energy in ${}^3_\Lambda\mathrm{H}$ (B_Λ), the value of which suffers from large experimental as well as theoretical uncertainties, we conclude that none of the conflicting RHI measured lifetime values can be excluded, but rather implies its own constraint on B_Λ.

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Parallel I / 17

ΛNN input to neutron stars from hypernuclear data

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This work is a sequel to our two publications from 2023 (1,2) where 14 experimental 1s and 1p single-particle binding energies of Λ in hypernuclei led to a quite well-defined optical potential for the Λ-nucleus interaction. The potential contains a traditional linear density term and a quadratic density term, the latter representing ΛNN interaction, within an approach based on a simplest possible formulation. The present work reports on extending the above analysis to 21 data points input, including also 1d and 1f states in medium-weight and heavy hypernuclei. The upgraded results agree, within errors, with the earlier results and could indicate a direction towards solving the so-called hyperon puzzle in the core of neutron stars (3). We show that a need to suppress the ΛNN interaction involving an excess neutron and a core nucleon can be tested with a forthcoming experiment at JLab.

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Parallel I / 18

Chiral symmetry restoration deduced in precision spectroscopy of pionic atoms

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The latest results from the spectroscopy of deeply bound pionic Sn 121 atoms, performed at RIBF, RIKEN, are reported. The binding energies and widths of the pionic orbitals were determined, and the pion-nucleus interaction was deduced with unprecedented precision. It was found, after extensive analysis, that the chiral condensate at nuclear saturation density is reduced by a factor of 60+-3% (T. Nishi, K. Itahashi et al., Nature Phys. (2023) doi:10.1038/s41567-023-02001-x).
We also discuss the current status of systematic spectroscopy of pionic Sn isotopes and future plans to deduce the density dependence of the chiral condensate.

Poster / 19

3D Simulation studies of mixed plasma confinement at AEgIS

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3D Simulation studies of mixed plasma confinement at AEgIS
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Abstract

The AEgIS (Antimatter Experiment: Gravity, Interferometry and Spectroscopy) project, based at CERN's Antiproton Decelerator (AD) facility, has undergone significant enhancements, capitalizing on the increased quantity of colder antiprotons made available by the new Extra Low Energy Antiproton Ring (ELENA) decelerator. These improvements aim to create a horizontal pulsed beam of antihydrogen atoms and enable a direct investigation into the impact of gravity. This experiment seeks to probe the Weak Equivalence Principle for antimatter.

The AEgIS experiment involves a trap comprising circular electrodes set within both a 5T and a 1T axial magnetic field. The 5T field serves the purpose of capturing cold antiprotons, while the 1T field facilitates the production of antihydrogen. In order to maximize the anti-hydrogen formation, it is crucial to have a detailed understanding of the properties of trapped antiprotons, which can be achieved by realistic 3D simulation studies in for the dynamics of particle confinement. Previous studies indicated that antiprotons exhibit greater stability in a shallower potential well. In this work, we examine the dynamics of antiprotons by varying the outer electrode potentials while maintaining constant potentials at the inner electrodes of the electrostatic trap, utilizing a Particle-In-Cell (PIC) solver in CST studio. We extended the studies on the temporal evolution of a mixed plasma generated with the introduction of electrons inside the trap along with the antiprotons by observing the effect of their initial properties: initial density, temperature and number of macro-particles. Additionally, we provide an overview of the results obtained for temperature and profile evolution for electrons and antiproton using a rotating wall electrode.Finally, we summarize our plans to develop a full digital twin of the AEgIS experiment over the next two years, providing valuable insights into the parameters required for optimized experiments.

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Parallel I / 20

High-sensitivity searches for matter-antimatter conversions at the European Spallation Source

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The HIBEAM/NNBAR program is a proposed two-stage experiment at the European Spallation Source (ESS) to search for baryon number violation [1]. The goal of the program is to produce new insights into the origins of baryogenesis by performing searches for neutron–antineutron oscillations, increasing the sensitivity by three orders of magnitude compared with the previously established limit from the Institut Laue-Langevin (ILL) [2].

The first stage of the program, HIBEAM (High-Intensity Baryon Extraction and Measurement), will utilize the fundamental physics beamline during the early stages of ESS operation [3]. It represents the first search for neutron to antineutron oscillations at a spallation source. Already in this stage, searches with world-leading sensitivity can be conducted. The neutron extraction system for this project is currently under construction and expected to be installed at the ESS next year.

NNBAR will make use of the Large Beamport in the ESS target station monolith, specifically designed for this experiment. Apart from unprecedented intensities of slow neutrons, the experiment requires a magnetically shielded beamline, novel neutron reflectors and a state-of-the-art detector system to reach its sensitivity goal. The annihilation detector needs to be able to identify the multi-pion final state produced in the annihilation of an antineutron in a carbon target. The Conceptual Design Report of the experiment has recently been published [4].

A general overview over the HIBEAM/NNBAR program will be given and the current status of both experiments as well as their beamline and detector designs will be presented.

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Muonic Helium Hyperfine Structure Measurements at J-PARC MUSE

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Muonic helium is a hydrogen-like atom composed of a helium atom with one of its two electrons replaced by a negative muon. Its ground-state hyperfine structure (HFS), which results from the interaction of the negative muon magnetic moment and the remaining electron, is very similar to muonium HFS but inverted. Precise measurements of the muonium ground-state HFS interval using a microwave magnetic resonance technique are now in progress at J-PARC by the MuSEUM collaboration [1]. The same method can be used to precisely determine the muonic helium HFS and the negative muon magnetic moment and mass. The world's most intense pulsed negative muon beam at J-PARC Muon Science Facility (MUSE) allows improving previous measurements and testing further CPT invariance by comparing the magnetic moments and masses of positive and negative muons (second-generation leptons). Moreover, a more precise determination of the muonic helium atom HFS will be beneficial to test and improve the theory of the three-body atomic system.
Already, new precise measurements of the muonic helium HFS were performed at zero magnetic field using the high-intensity pulsed negative muon beam at MUSE D-line. Our new result is more precise than both previous measurements at weak and high fields [2,3] done 40 years ago and the first one performed with CH4 admixture (previously Xe) as an electron donor to form neutral muonic helium atoms [4].
High-field measurements are now in preparation at MUSE H-line, using ten times more muon beam intensity than at the D-line, and with decay electrons being more focused on the detector due to the high magnetic field, we aim at improving the accuracy of previous measurements nearly hundred times for muonic helium HFS.
Furthermore, a new experimental approach to recover the negative muon polarization lost during the muon cascade process in helium is being investigated by repolarizing muonic helium atoms using a spin-exchange optical pumping (SEOP) technique [5], which would drastically improve the

measurement accuracy, and where a direct improvement by a factor of ten may be realized. The first laser repolarization experiments were recently performed.
An overview of the different features of these new muonic helium atom HFS measurements and the latest results will be presented.

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[3] C. J. Gardner *et al.*, Phys. Rev. Lett. **48**, 1168 (1982)
[4] P. Strasser *et al.*, Phys. Lett. **131**, 253003 (2023)
[5] A. S. Barton *et al.*, Phys. Rev. Lett. **70**, 758 (1993)

Poster / **22**

The scintillating bar detector of the ASACUSA experiment

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Detecting charged pions emitted from antiproton annihilation on nuclei is a well-established technique utilized to determine annihilation vertex positions, crucial also for several experiments in the antimatter field. For the past decade, a detector composed of plastic scintillating bars has been integral to the ASACUSA experiment, employed in both antihydrogen formation experiments and annihilation cross-section measurements. This work delineates its design and operations, encompassing a significant upgrade of the light readout system and front-end electronics implemented two years ago. Additionally, it validates the tests with cosmic rays and the improvements towards a better integration into the overall control system.

Poster / **23**

Supporting 3P0 Quark-Pair Creation using Landau Gauge Green' s Functions

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Phenomenological evidence suggests that strong decays of low-excitation hadrons often involve the creation of a light quark-antiquark pair with zero angular momentum, known as the 3P0 mechanism, derived from a scalar bilinear. Despite Quantum Chromodynamics being mediated perturbatively by spin-one gluons and ex- hibiting chiral symmetry in its Lagrangian, a scalar decay term appears spontaneously upon chiral symmetry breaking. We explore this by employing the quark-gluon vertex in the Landau gauge and the nonperturbative effects recently clarified, alongside a constant chromoelectric field similar to the Schwinger pair production in Quantum Electrodynamics. We compare this to a two-field insertion diagram in QED and argue that the relevant quantum numbers for discussing production are 3Σ0, 3Σ1, and 3Π0, analogous to those in diatomic molecules. Our results indicate significant contributions from the third decay mechanism, supporting the 3P0 phenomenology at momenta at or below the fermion mass scale. However, ultrarelativistic fermions predom- inantly exhibit 3Σ1 quantum numbers. In QED, 3Σ0 is dominant, whereas in QCD, 3Π0 prevails at sub-GeV momenta due to the requirement to form a color singlet.

Poster / **24**

Production of exotic onium states and atoms in photon-photon collisions at hadron colliders

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The cross sections for the production of different composite hadronic and leptonic objects in photon-photon fusion processes in proton-proton, proton-nucleus, and nucleus-nucleus ultraperipheral collisions at the CERN Large Hadron Collider (LHC) and Future Circular Collider (FCC), as well as in Au-Au collisions at the BNL Relativistic Heavy-Ion Collider (RHIC), are estimated. First, the production of three types of spin-even onium systems are considered: quarkonium (spin-0,2 meson resonances), dihadrons (including pionium, kaonium, protonium, and D-mesonium), leptonium (positronium, dimuonium, and ditauonium) states. Secondly, we discuss the production of charged lepton or meson pairs ($\gamma\gamma \to \mathrm{X}^+\mathrm{X}^-$ with $\mathrm{X}^\pm = \ell^\pm, \pi^\pm, \mathrm{K}^\pm, \overline{\mathrm{p}}$) followed by the capture of the negative particle by one of the colliding beam hadrons to form exotic atoms such as muonic, tauonic, pionic, and kaonic hydrogen and its counterparts with lead ions.

Parallel I / **25**

Formation of hydrogen-like Highly Charged Ions using antiprotonic atoms as pathway systems

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Recent simulations of the annihilation of antiprotons on the periphery of nuclei at the end of their cascade within antiprotonic atoms have highlighted the possibility of trapping (and cooling) the resulting fully stripped (highly charged) nuclear remnants. In addition to being a novel pathway for forming and trapping (even short-lived) radio-isotopes, these open the door to employing them as the starting point for a charge exchange process with Rydberg positronium or Rydberg atoms, and thus forming long-lived Rydberg states of single-electron highly charged ions (HCI's). Both transitions between Rydberg states and between the HFS sub-levels of the ground state that these ionic systems reach at the end of their cascade has the potential to test QED and search for BSM physics in a novel manner.

Poster / **26**

Towards g-factor measurements of (anti-)protons using techniques based on quantum logic spectroscopy

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High-precision matter-antimatter comparisons allow to test CPT symmetry and to search for new physics beyond the standard model. The BASE collaboration contributes to these tests by measuring the charge-to-mass ratio and g-factor of protons and antiprotons in cryogenic Penning traps [1-3]. The BASE experiment at the Leibniz University Hannover is developing measurement schemes based on sympathetic cooling and quantum logic spectroscopy to further increase sampling rates, using ^{9}Be$^+$ both as cooling and logic ion [4].

This contribution will present recent advances, including adiabatic transport in the ms-regime [5] and ground-state cooling of a single ^{9}Be$^+$ ion [6]. Furthermore, upcoming changes to the experimental apparatus, including a redesigned Penning trap stack, will be shown.

[1] G. Schneider et al., Science 358, 1081 (2017) [2] C. Smorra et al., Nature 550, 371 (2017) [3] M.J. Borchert et al., Nature 601, 53 (2022) [4] Juan M Cornejo et al 2021 New J. Phys. 23 073045 [5] Meiners et al., arXiv:2309.06776 (2023) [6] Cornejo et at., arXiv:2310.18262 (2023)

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Novel super-thermal exotic atom beam for the measurement of the gravitational acceleration of muonium

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The LEMING experiment aims to measure the gravitational free fall of muonium (Mu = $\mu^+ + e^-$), a purely leptonic, exotic atom. The experiment will be a unique probe to test the weak equivalence principle on elementary, second generation antimatter using a system without large contributions to the mass from the strong interaction.
The experiment will employ atom interferometry using a three-grating interferometer, which relies on a novel, cold vacuum Mu source with a narrow energy and transverse momentum distribution. We have demonstrated the working principle of such novel source based on Mu conversion of conventional muon beams in a thin layer of superfluid helium, that provided ~ 8 % conversion efficiency to an atomic beam with $\sim$ 25˜mrad angular divergence. Such a Mu beam may be amenable to atom interferometry measurements that would provide a $\sim$ 1% precision on the gravitational acceleration of Mu, and furthermore, has the potential to improve the fractional precision of Mu 1S-2S measurements.
In this contribution the LEMING experiment will be introduced and measurements on the first observation of Mu emitted from superfluid helium and an initial characterization of the novel Mu source will be presented. Prospects of this newly developed atomic Mu beam from superfluid helium in the context of future gravity and spectroscopy experiments will be discussed.

Poster / 28

Interferometer for the LEMING experiment

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A high quality superthermal muonium beam (bound e^-/μ^+) has recently been developed, which might be amenable for atom interferometry, and next generation laser spectroscopy experiments.
Here we provide an overview into the design and development of the first interferometer prototype, together with the theoretical expectations of sensitivity.
A Talbot-Lau interferometer is being designed for this purpose, where the vertical phase of the interferogram encodes the gravitational acceleration of the atoms, which will be sampled by scanning the third (masking) grating.
The main challenges include strict control over vibrational, displacement, and alignment constraints of a sub-nm measurement.

Parallel I / **29**

Towards Lamb shift spectroscopy of antihydrogen atoms at the GBAR beam line

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We have proposed a spectroscopic study of antihydrogen (H) Lamb shift using a neutral antiatomic beam at keV energies. Direct spectroscopy of the $n = 2$ Lamb shift transition of H atoms would enable the first measurement of the antiproton ($\bar{p}$) charge radius. Recently, the GBAR experiment demonstrated the production of 6.1 keV H atoms via a charge exchange reaction of $\bar{p}$ passing through a positronium cloud, which can be utilized for Lamb shift spectroscopy. An experimental setup has been developed for the GBAR experiment.

The spectrometer comprises two consecutive microwave (MW) apparatuses and a Lyman-α photon detector. Each MW apparatus has a pair of parallel plate electrodes surrounded by a box to induce the Lamb shift transition. The detector counts the remaining $2S$ state H atoms.

We present the development of MW apparatuses, their MW characteristics, and their commissioning using hydrogen atoms. Further, we discuss the expected precision in the Lamb shift spectroscopy for H atoms.

Poster / **30**

Optical potential analysis of antiproton-nucleus data at low energy

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An analysis is conducted on both the elastic scattering and annihilation cross-sections of antiproton-nucleus data at low energy, aiming to identify shared parameters for a Woods-Saxon optical potential.
Given the limited data available at low energies, it is important to conduct new measurements in these energy ranges and using diverse nuclear targets to enhance our comprehension of the strong nuclear interaction. The outcomes of this data analysis provide insights into the energy regions that could be feasibly explored in future experiments at the Antiproton Decelerator facility at CERN.

Parallel I / **31**

An antiproton trap system using a drift tube accelerator and energy degrader

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The ASACUSA CUSP experiment upgraded the MUSASHI antiproton trap with a drift tube accelerator to receive antiproton beams from ELENA, which replaced the Radio-Frequency Quadrupole decelerator. ELENA provides antiprotons at a fixed energy of 100 keV. The drift tube adjusted the injection energy of antiproton beams for the thin energy degrader at the entrance of the trap by 19 keV. The number of cooled antiprotons in the MUSASHI trap reached 2 million per ELENA spil. We will discuss the trapping efficiency and the effect of the degrader materials.

Poster / **33**

Experimental Investigation of QED Effects through Antiprotonic Atom X-ray spectroscopy: first test beams with TES detectors and solid targets

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Experimental Investigation of QED Effects through Antiprotonic Atom X-ray spectroscopy: first test beams with TES detectors and solid targets

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Tests of our understanding of strong field quantum electrodynamics (QED) represent a key frontier in fundamental physics pursued by precision measurements. A new experiment called PAX (antiProtonic Atom X-ray spectroscopy), seeks to probe higher-order strong-field QED through precision spectroscopy of Rydberg states in antiprotonic atoms. The PAX project is possible due to slow antiproton beams now available at ELENA, and new pixeled Transition-Edge Sensor (TES) x-ray microcalorimeter detectors. TES detectors boast a 50x gain in intrinsic resolution over semiconductor methods, however these very sensitive quantum sensors have yet to be demonstrated with antimatter beams. The first step of the PAX project is to perform an in-beam test of a TES detector at ELENA by sending bunched antiprotons onto solid targets and measuring the resulting x-ray cascade with a prototype TES.

I will present the detailed design of this test setup both for beamline infrastructure and detector design, as well as first results from the 2024 beamtime with the target chamber and Ge detector used for overview spectroscopy and diagnostics. The first results will be compared with a complete GEANT4 simulation, and I will discuss the prospects of the full test beam planned for 2025.

Poster / 34

Prospects for forward emitted positronium from nanoporous membranes

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We present ongoing efforts to characterize forward-emitted positronium (Ps) from transmission positron/Ps converters. Utilizing innovative silicon membranes with pass-through nanochannels [1], we aim to build upon recent developments within the AEgIS collaboration. Our focus lies on understanding the velocity distribution of forward-emitted Ps and its interaction with ultraviolet (UV) laser light, with implications for future studies on Ps Bose-Einstein condensates, laser cooling within nano-cavities, and enhanced antihydrogen formation.
Preliminary investigations have demonstrated promising results, indicating up to 16% of positron to Ps conversion in transmission configuration for membranes with thicknesses of only 3.5 um [2]. By varying membrane thickness, nanochannel size, and positron implantation energy, we aim to defining the optimal conditions for maximizing Ps yield and controlling its velocity distribution. Furthermore, our study aims to assess the absorption properties of UV laser light by our transmission converters, offering insights into potential strategies for Ps manipulation and cooling.
These efforts offer potential for improving antihydrogen beam formation at AEgIS by enabling collinear installation without downstream obstacles. This integration can also lead to an exponentially increasing formation cross-section due to the co-propagating antiprotons and Rydberg-positronium atoms. Moreover, the membrane, when attached to a flat silicon surface, allows for the construction of a buried cavity enabling studies on laser-cooled positronium through a membrane, setting the stage for future studies on Bose-Einstein condensates with Ps.

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Searching for a dark matter particle with anti-protonic atoms

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Candidates for dark matter are proposed and searched from the sub meV to TeV scales. The indirect observations don't provide sufficient power to constrain to a narrow parameter space of the searches. One of the dark matter candidates, a deeply bound (uuddss) sexaquark, S, with mass in the GeV range is hypothesized to be long lived and very compact, described within the Standard Model of Particle Physics without extensions. S properties make it particularly challenging to explore experimentally.

In this contribution we will show an experimental scheme [1] in which S could be produced at rest through the formation of helium-3 antiprotonic atoms and their subsequent annihilation into S +K^+K^+ + pi^-. This channel is particularly clean as there is no other channel naturally populating the same final state. It can be uniquely identified both through the unique tag of a S=+2, Q=+1 final state, as well as through full kinematic reconstruction of the final state recoiling against it.

[1] M. Doser, G. Farrar, G. Kornakov, "Searching for a dark matter particle with anti-protonic atoms" , Eur.Phys.J.C 83 (2023) 12, 1149, arXiv:2302.00759 [hep-ph]

Parallel I / 36

Antihydrogen annihilation detection: the ALPHA-g radial TPC

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The recent measurement of the antihydrogen gravitational acceleration [Nature 621, 716–722 (2023)] relies upon the detection of the annihilation of the anti-atoms that are released from their magnetic confinement and that move under the influence of gravity. The ALPHA-g magnetic trap is surrounded by a Time Projection Chamber designed to identify the annihilation products and to reconstruct the annihilation position. The TPC is called "radial", or rTPC, because the drift field is perpendicular to the trap axis and, therefore, to the magnetic field of the external field. The design, construction and commissioning of this detector are the focus of this presentation.

Parallel I / 37

A New Technique to Measure the Axial and Transverse Energy of Trapped Antihydrogen Atoms during release from an Ioffe-Pritchard Magnetic Trap

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In the era of ever-increased precision measurements of the fundamental properties of antihydrogen at the ALPHA experiment at CERN, knowledge of the antihydrogen energy distribution has become vital; for example, it provided a significant contribution to the uncertainty in the first direct measurement of the gravitational acceleration of antihydrogen [1]. Increased precision in ALPHA's experiments can be achieved by reducing antihydrogen energy, but measuring the extent of achieved cooling is essential for optimization and simulation-experiment comparison. In recently demonstrated techniques of Doppler laser cooling [2] and adiabatic expansion cooling [3] of trapped antihydrogen, energy reduction is predominantly along the trap axis, with reduction in the transverse plane resulting from energy mixing due to details of the trap magnetic fields [4]; highlighting the importance of knowledge of energy in both axial and transverse dimensions. Further, in some antihydrogen spectroscopic experiments, the dominating lineshape broadening effect depends on the axial energy [5], whereas for others it depends on the transverse energy [6].

Currently, antihydrogen energy is measured using pulsed laser light to excite a transition to an untrappable state [2], and measuring the time taken for the anti-atom to annihilate with the trap wall. This time-of-flight method gives access to the transverse energy; in principle, the axial energy can be accessed by sweeping the laser detuning to determine the spectral lineshape. However, the existence of a multitude of line-broadening mechanisms prevents a straight-forward reconstruction of the axial energy. Further, measuring the energy using this method takes several hours and relies on the availability of the pulsed laser light.

In ALPHA, antihydrogen is confined in an Ioffe-Pritchard magnetic trap, where an octupole provides radial confinement and solenoids on the left and right of the trapping region provide axial confinement. We demonstrate a technique to measure the axial and transverse energies of a population of trapped antihydrogen atoms via a controlled rampdown of the octupole magnetic field (keeping the solenoid fields static). During this process, the trap depth gradually decreases, resulting in annihilations on the trap walls that can be resolved in space and time by ALPHA's silicon vertex detector. This technique relies on the principle that lower energy antihydrogen can be confined by a shallower magnetic trap, causing these anti-atoms to annihilate later in time. However, we show that a correlation of the axial and radial confining potentials means the axial annihilation location can be combined with the annihilation time to enable a measurement of both the axial and transverse antihydrogen energy just before annihilation. Since this energy differs from energy prior to release due to radial adiabatic expansion cooling, we present a modified version of a technique in Ref. [7], in which we use simulations of the octupole rampdown technique to reconstruct the axial and transverse energy prior to release using annihilation information.

We present experimental annihilation-data of both uncooled and laser-cooled antihydrogen atoms undergoing an octupole rampdown, and compare these results to simulations of the experimental procedure. This annihilation data is used to reconstruct the axial and transverse energy distributions of the experimental antihydrogen populations in typical confining potentials, showcasing the temperatures reached using ALPHA's current laser cooling methods. Finally, we compare the reconstructed transverse energy to the equivalent quantity determined using existing time-of-flight methods. This work makes it possible to measure distributions of both components of the antihydrogen energy in 10s of seconds.

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Poster / **38**

Detecting eV electrons at sub-kelvin temperatures for the LEMING experiment

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The LEMING experiment aims to test weak equivalence in leptonic antimatter using a novel cold muonium beam, that we recently synthesised from superfluid helium. For this experiment, it is paramount to operate particle detectors at temperatures below 1K, partially in the superfluid environment. The cryogenic detectors need to be capable of tracking positrons from decaying muons in a large solid angle and at a spatial resolution of ˜1mm, in coincidence with the low-energy atomic electrons released in the same process. Efficiency and background suppression capabilities of this detector system directly impact the sensitivity of the final measurement. We have demonstrated efficient and reliable sub-kelvin positron detection with commercial silicon photomultipliers (SiPMs) coupled to thin scintillator segments. Presently, we are working on a silicon-strip-based tracker system, further increasing spatial resolution and solid angle coverage. To detect the eV-range atomic electrons, we collect and accelerate them towards a low-threshold detector with an electric field of a few kV. We have obtained promising results using perovskite nanocrystals for this purpose, and are currently evaluating commercial superconducting nanowire single-photon detectors (SNSPDs). This talk or poster will focus on the cryogenic particle detectors of the LEMING experiment, in particular the characterisation of commercial SiPMs as well as novel perovskite scintillators below 1K.

Poster / **39**

Background Rejection for the ALPHA-g Anti-Hydrogen Detectors

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The ALPHA-g experiment recently made the news for the first direct measurement of the gravitational free-fall of anti-hydrogen. Crucial to this milestone is a detector system capable of accurately recording the vertical position of annihilating anti-atoms, with two critical requirements: precise localization of anti-hydrogen annihilations into the "up" or "down" regions, and effective discrimination against the cosmic ray background.

To accomplish this, the annihilation products are tracked using a radial time projection chamber detector, and fitted to a common vertex. Simultaneously, a secondary barrel scintillator detector

records the time of flight of these products. This timing information is used as part of a multivariate analysis to reject externally incident cosmic rays.

This presentation showcases the cosmic ray background rejection used in the published measurement, as well as the calibration and analysis campaign to unlock time-of-flight-based background rejection for forthcoming ALPHA-g measurements of the gravitational behavior of anti-hydrogen.

Parallel I / 40

The neutron-antineutron oscillation and low-energy antinucleon-nucleus interactions

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The neutron-antineutron oscillation violates baryon number conservation and is of great importance in the context of testing Grand Unified Theories and understanding the origin of the baryon asymmetry in the universe [1].

Currently, the oscillation time is constrained to be $> 0.86 \times 10^8$ s for free neutrons, and $> 2.7 \times 10^8$ s for bound neutrons [2,3]. In view of experiments planned in future facilities aimed at improving the limit with free
neutrons, recent proposals have been made that would substantially improve the sensitivity of the experiment with accurate understanding of the nuclear potentials experienced by low-energy antineutrons [4,5].

In this context, there is a renewed interest in the antinucleon-nucleus interaction. The data currently available are mainly from antiprotonic atom spectroscopy and antinucleon-nucleus scattering/annihilation cross-section measurements. The optical potential model developed well reproduces available experimental data of antiprotonic atom and scattering data. However, it has been pointed out that it still lacks full experimental verification [6].

In this presentation, the above topics are reviewed, and antiproton experiments that can potentially be conducted in this
context will be discussed.

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Parallel I / 41

First measurement of X-rays from resonance states of muonic deuterium molecule using a cryogenic detector

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By using a superconducting transition-edge-sensor (TES) microcalorimeter with ultra-high resolution $\Delta E \sim 5$ eV (FWHM), a spectroscopic measurement of $dd\mu^*$ was successfully performed for the first time.

The $dd\mu^*$, in which μ^- is resonantly coupled with two deuterons, is predicted by the latest few-body calculations to emit dissociative X-rays with characteristic continuous distribution in the range of $1.60 - 1.97$ keV depending on its quantum state and to dissociate. These resonance states have attracted attentions in atomic physics and studied theoretically [1] because they can play an important role in muon catalyzed fusion (μCF). By introducing the reaction mechanism via the resonance states of muonic molecules ($dt\mu^*,\ dd\mu^*$) in the μCF process, the temperature dependence in the μCF cycle, which has not been understood before, was explained theoretically[2]. A muCF model that includes the formation and decay of these resonance states ($dt\mu^*,\ dd\mu^*$) can reproduce temperature dependence of μCF cycle rate at various deuterium-tritium mixing ratios.

Since the energy band of the dissociative X-rays ($1.60 - 1.97$ keV) is close to the $2p - 1s$ transition X-rays (1.97 keV) of $d\mu$ atoms, which are unavoidably mixed in the energy spectrum, a conventional semiconductor detector ($\Delta E \sim 100$ eV (FWHM)) hardly separates the origins of these X-rays. Thus, we performed an X-ray spectroscopy experiment on $dd\mu^*$ in February 2023 at the J-PARC MLF D2 beamline using the TES detector.

The energy resolution was sufficient not only to separate $d\mu$ atoms $2p - 1s$ X-rays and dissosiative X-rays of $dd\mu^*$ but also to separate the vibrational and rotational quantum states of $dd\mu^*$ from the obtained spectrum. Dissociative X-rays show an energy spectrum that strongly reflects the shape of the wavefunction, allowing spectroscopic measurement to investigate the quantum states of the resonance states.

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Parallel I / 42

Hypernuclei Production through Antiprotonic Atoms

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The decay of antiprotonic atoms may lead to the formation of hypernuclei that can be produced via strangeness exchange reactions following the antiproton-nucleon annihilation. To estimate the

hypernuclei yields that can be expected by these kind of reactions, simulations were performed within the GiBUU transport framework.
Using ^{16}O, ^{40}Ar, ^{84}Kr and ^{132}Xe as target nuclei, it was shown that the formation of antiprotonic atoms provides access to currently undiscovered hyperisotopes with typical production rates of 10^{-5} to 10^{-4} per annihilation per hypernucleus. In this contribution, the results of recent calculations will be detailed [1]. The experimental requirements to investigate hypernuclei at ELENA produced in this way will be discussed.

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Future Perspectives of AD-ELENA Facility at CERN

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The Antimatter Factory at CERN focuses on producing low-energy antiprotons for high-precision antimatter experiments. It comprises the Antiproton Decelerator (AD), which is an adaptation of the '80s Antiproton Collector (AC), and the recently commissioned Extra Low ENergy Antiproton ring (ELENA), which became fully operational in 2021. Initially, the AD could support only a single experiment at a time, typically in eight-hour shifts, delivering approximately 3e7 antiprotons at 5.3 MeV with a two-minute repetition period. Currently, with the integration of ELENA, the facility can supply four bunches of 1e7 antiprotons each at 100 keV, maintaining the same repetition period, and is capable of serving up to four experiments simultaneously or more in a sequential round-robin arrangement. The introduction of ELENA has significantly enhanced performance, suggesting new possibilities for low-energy antimatter physics research. This progress, along with the increasing complexity of the facility, calls for a thorough review of its consolidation strategy to ensure its longevity. Moreover, it presents an opportunity to contemplate future upgrades to meet the evolving demands of the scientific community. This presentation will detail the present performance and will explore feasible upgrade options for the current facility.

Parallel I / 44

Perspectives of testing discrete symmetries and quantum entanglement in decays of positronium with the total-body J-PET scanner.

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The Jagiellonian Positron Emission Tomograph (J-PET) is the first PET scanner based on plastic scintillators [1]. It is designed to measure momentum vectors and the polarization of photons originating from the decays of positronium [2,3]. In combination with the newly invented positronium imaging method [4], J-PET enables the study of discrete symmetries in positronium without the use of magnetic fields [5.6]. We will present the newest results of P, T, CP, and CPT symmetry studies with the 192 plastic strip J-PET detector [7], explain the method of positronium imaging, and present the first results of quantum entanglement correlations of photons from the annihilation of positronium. We will also present the status of the construction of the total-body J-PET facility in Poland [8,9]. The

total-body J-PET system is designed as a modular detector with a length of 250 cm and a diameter of 80 cm, which will increase the sensitivity of positronium decay studies by two orders of magnitude compared to the currently achieved results.

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Poster / **45**

A cyclotron trap for antiprotonic atom x-ray spectroscopy in gaseous targets

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Quantum electrodynamics (QED) is a foundation of modern physics, whose detailed study is one of the frontiers for Beyond Standard Model searches. In this domain, new physics may appear as minute differences between theory and experiments, accessible with extremely high precision QED tests. While extensive studies have been performed for light systems (hydrogen, antihydrogen, muonic hydrogen, etc.), few high precision measurements exist for high-Z systems with extremely high Coulomb fields.

Decades of work has sought to study this strong-field QED regime via spectroscopy of highly charged ions (HCI) [1, 2]. These systems, however, are plagued by high theoretical uncertainty in the transition energies due to poorly-known nuclear radii, which clouds high-order QED contributions. In order to circumvent such issues, novel studies have been proposed involving exotic atoms, where the orbiting electrons are replaced with a more massive particle, such as a negatively charged muon (μ^-) [3] or antiproton ($\bar{p}$) [4]. In these exotic systems, a special class of Rydberg transitions can be found where QED effects are large, while nuclear uncertainties are negligible, making them prime candidates for high-precision strong-field QED tests [5].

The PAX experiment is a new effort to study Bound State QED (BSQED) in antiprotonic systems, where a range of gaseous elements will be subjected to a low-energy antiproton beam, coming from CERN's Extra Low Energy Antiprotons (ELENA) ring, leading to $\bar{p}$ capture in circular Rydberg states, followed by a cascade of Auger and radiative transitions, expelling the remaining electrons and resulting in hydrogen-like antiprotonic systems [4]. In order to assure this, it is necessary to mitigate the electron refilling by using a low-pressure gaseous cell to slow down and capture the antiprotons.

A novel cyclotron trap is currently being designed, with tools such as COMSOL®and GEANT4, in order to be implemented in PAX. Composed of two iron-core coils, the generated magnetic fields of 0.5 T in the interaction region are able to trap the incoming 100 keV antiproton beam, degraded to 10 keV, and slow it down in the process, until capture occurs and the subsequent cascade of x-ray transitions is measured with a state-of-the-art Transition Edge Sensor (TES) detector [6]. Aside from

the trap itself, the simulation incorporates realistic particle scattering and
deceleration, as well as the necessary charged particle optics to control a highly dispersive beam.

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Poster / **46**

Multi-Photon decays of positronium with J-PET

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Being governed by electromagnetic (EM) interaction, the bound state of electron and positron forms a metastable state-Positronium (Ps). Ps is hydrogen-like atom, free from any hadronic background as well as any weak interaction effects. Being a leptonic system, it is governed by Quantum Electrodynamics (QED) because of which accurate theoretical predictions can be made and put to stringent test [1]. Test for bound state QED could be carried out by probing the decay rates of Positronium. In particaular the Ps triplet state, the ortho-Positronium (o-Ps), which predominantly decays into three gamma quanta. The rate for o-Ps decaying into a higher number of photons is by six orders of magnitude smaller as expected from QED calculations [1, 2, 3]. However, higher decay channels could be probed using the multi-purpose Jagiellonian PET (J-PET) detector. J-PET is a plastic-scintillator based, multi-discipilinary PET tomograph [3, 4, 5] extending its reach from biomedical application to active fundamental studies like CPT invariance, photon entanglement and mirror matter searches.

J-PET aims to study the contribution of multi-photon decays in the context of the invisible mirror matter study. Mirror matter is a hypothetical particle to restore parity invariance. Study of multi-photon decays of ortho-Positronium empower us to have better control over the exploration of this invisible particle. The branching ratio of $o - Ps \to 5\gamma$ experimentally [6] determined in previous experiments is by several orders of magnitude less precise than the theoretical calculation [7]. In this work we will present the capabilities of J-PET and preliminary studies of the multi-photon decays of ortho-Positronium and aim to put stringent limits in this rare decay.

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Poster / **47**

Analysis results of the search for neutron to mirror-neutron oscillations at PSI

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Mirror matter was initially proposed as a possible fix of parity violation in the weak interaction on a global scale[1]. More in general, mirror matter and mirror neutrons in particular could help explain baryon number violation and are viable candidates for dark matter[2].
The mirror-neutron experiment at PSI was a storage measurement, designed to search for anomalous disappearances of ultracold neutrons in the presence of a controlled non-zero magnetic field[3]. The experiment completed operation 2021 and tested a mirror magnetic field from about 5 μT to above 10 μT, finding no evidence for anomalous neutron losses. We provide an in-depth look at the analysis based on Monte Carlo simulations and precise magnetic field maps and present new limits on the oscillation time.

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Poster / **48**

Mirror Matter in Positronium Decay Searches with the J-PET Detector

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Positronium (Ps) atom, consisting of an electron and a positron bound together, represents a unique and intriguing system for fundamental physics research. This composite particle offers an exceptional opportunity for conducting precise tests, owing to its properties that are accurately described by Quantum Electrodynamics (QED) within the framework of the Standard Model (SM). Moreover, the decay processes of positronium, which can be modeled through Monte Carlo techniques, offer valuable insights into various aspects of particle physics. The development of a novel tomography system based in scintillator detectors at the Jagiellonian University, the J-PET setup [1], with high angular and timing resolutions, allows us to perform multi-disciplinary studies involving fundamental tests of physics, medical research, quantum entanglement measurements [2,3], and enhances our ability to study positronium decays in search of potential Dark Matter candidates, one of the unresolve mysteries of the current SM framework.

We present current searches of Dark Matter (DM) involving ortho-Positronium (o-Ps) decays by means of the J-PET detector. The main aim of this work is to search for Mirror Matter, a new type of matter proposed to restore the parity invariance and plausible candidate for the DM component of the Universe. The study tries to push the actual limits in the precision measurement of the lifetime of the o-Ps decay to three gamma quanta to compare to the accurate QED description in search of the elusive DM [4].

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Measurement of the C-forbidden $2\,^3\mathbf{S}_1 \rightarrow 2\,^1\mathbf{P}_1$ transition in positronium

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We report the results of a new measurement of the $2\,^3\mathrm{S}_1 \rightarrow 2\,^1\mathrm{P}_1$ transition (ν_F) in positronium (Ps). Though this transition is forbidden by charge conjugation symmetry (C), it can be observed in a magnetic field. We optically excite Ps from a pulsed beam to produce radiatively metastable $2\,^3\mathrm{S}_1$ atoms and drive them to the $2\,^3\mathrm{P}_1$ level in a rectangular waveguide using microwave radiation. The C-allowed $2\,^3\mathrm{S}_1 \rightarrow 2\,^3\mathrm{P}_1$ transition (ν_1) was also measured in the same waveguide, using the same techniques, and the observed Zeeman shift was used to determine the local magnetic field strength. The measurements were performed in a range of magnetic fields, making it possible to determine the field-free ν_1 and ν_F transition frequencies, and to set limits on the C-forbidden transition matrix element $|\langle 2\,^1\mathrm{P}_1|H_{CP}|2\,^3\mathrm{P}_1\rangle|$

Parallel I / **50**

Spectroscopy of η'-mesic nuclei with 12C(p,dp) reaction at GSI/FAIR

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The possible existence of η' meson nucleus bound states (η'-mesic nuclei) has been attracting interests both theoretically and experimentally, since in-medium properties of the η' meson are closely related to the axial $U(1)$ anomaly and the chiral symmetry in QCD. The especially large mass of the η' meson (∼958 MeV/c^2) compared with the other light pseudoscalar mesons is theoretically explained by an interplay between the axial $U(1)$ anomaly and spontaneous breaking of chiral symmetry in the QCD vacuum. In the nuclear medium, where chiral symmetry is partially restored, the η' meson mass is expected to be reduced. Such a mass reduction would lead to an attractive η'-nucleus potential, suggesting the existence of bound η'-mesic nuclei. In two experiments to search for η'-mesic nuclei, previously performed by using the (p,d) reaction and the (γ, p) reaction, no significant signal of the η'-mesic nuclei was observed due to the limited experimental sensitivities.

We have recently performed a new spectroscopic experiment of the ^{12}C(p,dp) reaction in order to search for η'-mesic nuclei with an increased experimental sensitivity. We have integrated the WASA central detector into the fragment separator (FRS) at GSI. A 2.5 GeV proton beam impinged on a carbon target to produce η'-mesic states via the ^{12}C(p,d)^{11}C$\otimes\eta'$ reaction. The missing mass of the reaction is obtained by measuring the deuteron momenta with FRS used as a forward high-resolution spectrometer. Simultaneously, possible decay particles from the η'-mesic nuclei, especially high-momentum protons ($\sim$1 GeV/c) emitted in the decay via the two-nucleon absorption process, are identified with the WASA detector system surrounding the reaction target in order to improve the signal-to-background ratio of the missing-mass spectrum. First data taking was successfully accomplished in February 2022. In this contribution, preliminary results of this experiment and future prospects will be discussed.

Poster / **51**

Exploring the Polarization Correlation of Photons Emitted from Positron Annihilation in a Porous Medium

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Quantum Electrodynamics (QED) postulates that the photons emitted during the self-annihilation of the singlet state of positronium atoms (Ps) in a vacuum are maximally entangled in their polarization [1]. Despite theoretical support for this behavior, experimental verification has proven to be challenging [2,3]. This challenge may arise from the interference of alternative decay processes, such as direct positron-electron annihilation, the decay of the triplet-state of Ps via the pick-off process, or its conversion to singlet state via spin-exchange reactions with paramagnetic molecules such as O_2 [4], induced by the medium. In this study, we investigate the potential of the J-PET detector to explore the polarization correlation of two photons generated from positron annihilation in a porous medium. Constructed with plastic scintillators, it allows for the estimation of photon polarization via Compton scattering [5-7]. The inclusion of positron lifetime as an additional parameter serves to differentiate between decay processes, thus aiding in the examination of photon polarization correlation as a function of positron lifetime inside the medium. Understanding this correlation not only contributes to our fundamental knowledge of entanglement in the high-energy domain but also holds potential for advancements in PET imaging techniques [3,4].
In my presentation, I will outline the key features of the J-PET detector, with a particular emphasis on its capacity for measuring the polarization of high-energy photons [8]. Furthermore, I will present the results observations concerning the polarization correlation of photons produced from positron annihilation within a porous medium, leveraging the assessed lifetime of positrons.
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Poster / **52**

Prospects for improving the sensitivity of CPT symmetry test in positronium decays with J-PET

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One of the enduring challenges in fundamental physics is rigorously quantifying deviations from, or upholding the exactness of, discrete symmetries observed in nature. Measurements of angular correlations in the decays of polarized positronium (Ps) provide a sensitive probe for testing CPT symmetry in the electroweak interactions [1]. Due to its unique nature as the lightest bound state of an electron and its antiparticle, Ps plays a critical role in searches for CPT violation. The Jagiellonian Positron Emission Tomograph (J-PET) detector, employing plastic scintillators, facilitates high-precision measurements of these angular correlations in Ps decays [2]. J-PET has demonstrably achieved a sensitivity level of 10^{-4} in its initial CPT symmetry test [3], which involved searching for non-vanishing CPT-violating correlations between the spin of polarized $^3S_1$ positronium and the momenta of its annihilation photons. Notably, J-PET has also established stringent limits on the CP symmetry test using the polarization of photons [4]. This work explores avenues for further enhancing the sensitivity of the CPT symmetry test by increasing the ortho-positronium (o-Ps) detection efficiency with a new detector prototype.

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Precision studies of ortho-positronium decay rate with J-PET

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Positronium atom (Ps), a fascinating purely leptonic system, serves as an excellent testbed for probing quantum electrodynamics (QED) in the bound state [1, 2]. Ps can manifest in one of two states, depending on the total spin number (S): a short-lived state with spin zero (para-Ps) and long-lived meta stable state with spin one (ortho-Ps). Prior to 1995, a significant discrepancy existed between experimentally measured and QED-predicted lifetimes values, termed as the ortho-Ps lifetime puzzle, which was later attributed to pickoff annihilations occurring during the thermalization process [3, 4]. Several groups have experimentally estimated the ortho-Ps decay rate in vacuum, yielding the most precise value of $\boxtimes_3$ = 7.0401 ± 0.0007 μs^{-1} [5]. However, this remains two orders of magnitude less precise than the theoretical prediction [6, 7].
This study proposes a novel methodology for estimating the ortho-Ps decay constant by measuring the 3γ and 2γ decay rates as a function of time utilizing J-PET, a multimodule detector capable of simultaneous multiphoton registration [8-10]. The primary aim of this investigation is to significantly improve the accuracy of determining the decay rate of ortho-Ps compared to previous measurements. The forthcoming presentation will emphasize the adapted analysis algorithm and highlight the results, which have already shown a precision that is an order of magnitude better than the best value measured so far.

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Parallel I / **54**

Towards a direct hydrogen-antihydrogen comparison

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The gravitational and spectroscopic properties of antihydrogen are being measured with ever increasing precision. The limits for such experiments are not expected to come from the measurement resolution, but rather from hard-to-characterise systematic effects. These could be overcome by directly comparing hydrogen and antihydrogen, i.e. measuring both species in the same trap, using the same lasers, and (at least on average) at the same time. Such a comparison requires a compatible hydrogen source and a suitable detection scheme.

I will present the results of a 1s-2s experiment with laser cooled antihydrogen, conducted using a measurement technique compatible with both hydrogen and antihydrogen. The scheme relied on ionising the atoms from the 2s level, recapturing the ions (antiprotons) in a nested Penning trap, and detecting them using a microchannel plate detector. I will also present a scheme to produce cold hydrogen atoms via threshold photodissociation of sympathetically cooled BaH+ molecular ions, and report on experimental efforts to realise this technique. The ion trap nature of the scheme makes it well suited for use in antihydrogen experiments.

Poster / **55**

Antiproton-induced nuclear fragmentation

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One of the compelling areas of focus in nuclear and atomic physics are isotopes and isomers of different atoms. Many different isotopes are highly desired for experimental studies; however, accessing them is challenging with existing methods. A novel method that involves antiprotonic atoms has been suggested in [1]. In this method, the creation of isotopes is achieved by forcing the annihilation of the antiproton ($\bar{p}$) inside the antiprotonic atom [2]. The annihilation of $\bar{p}$ with one of the nucleons inside the nuclei produces mainly pions, from which some are captured by the remainder nucleus, leading to nuclear fragmentation.
This production path provides a significant yield of short-lived isotopes. Furthermore, the method requires the entire process to be executed directly inside an ultra-high vacuum system within an electromagnetic trap, allowing for the possibility of re-trapping previously unavailable atomic species, immediately upon their production with ns time precision.
The focus of this contribution is a further study conducted of the GEANT4 simulation data. We suggest a better assessment of the trappable fragments from the antiproton-induced fission. We also propose an advanced technique for obtaining access to some of the most intangible isotopes of interest and their isomers.

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Parallel I / 56

A Novel Low-Energy Ion Source: Production and Trapping of H- Ions for H/Hbar Comparison

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The ALPHA experiment (CERN) performs precise tests of fundamental Physics using spatially confined samples of antihydrogen atoms ($\bar{\mathrm{H}}$). For a direct $\mathrm{H}-\bar{\mathrm{H}}$ spectroscopic comparison, methods for loading atomic hydrogen into the apparatus are being considered. In this direction, we have demonstrated a novel source for low energy ions, capable of producing electrons, anions and cations. The source is based on the Matriz Isolation Sublimation technique, where the plume resulting from the laser ablation of a solid precursor is directed towards a sublimating inert gas matrix. Using a solid LiH target and a Ne matrix, we were able to produce samples consisting of electrons, $\mathrm{H}^{\pm}$ and $\mathrm{Li}^{\pm}$. Axial energy distributions peaked at values between 0 and 25 meV were observed following the capture of these particles in a Penning trap. A new version of the apparatus is being built to demonstrate the scalability of the technique. Such a source can be integrated into the ALPHA apparatus, where low energy H^{-} ions can be guided to the $\bar{\mathrm{H}}$ trapping region using the existing charged-particle magnetic transport system.

Parallel I / 57

Calculation of integration and disintegration processes of antihydrogen positive ions in collisions with positronium

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Antihydrogen positive ions ($\bar{\mathrm{H}}^{+}$) consisting of an antiproton and two positrons are utilized to produce cryogenic antihydrogen atoms. The $\bar{\mathrm{H}}^{+}$ can be collected with an electric field, sympathetically cooled by lasers with Be^{+} ions, and subsequently neutralized by stripping off one of the positrons. The $\bar{\mathrm{H}}^{+}$ is integrated in the mixture of antihydrogen ($\bar{\mathrm{H}}$) and positronium (Ps), but disintegrated by the collisions off Ps. Experiments producing the $\bar{\mathrm{H}}^{+}$ ions using laser-excited Ps targets are under development in the GBAR project at CERN.

In this study, we calculate the integration and disintegration processes of antihydrogen positive ions by a coupled-rearrangement-channel approach with a Gaussian expansion method. We investigate scattering cross sections between the antihydrogen atom and excited positronium for the integration processes, and those between the antihydrogen positive ion and positronium for the disintegration processes. The state-to-state reaction cross sections are obtained by S-matrix elements for all allowed scattering processes, namely both in forward and reversed directions, without the assumption of the detailed balance.

For the integration reaction, we include all possible inelastic processes: Ps excitation, Ps deexcitation, and Ps polarization where only the angular momentum of Ps changes without kinetic energy change [1]. The threshold behavior of these cross sections is also investigated [2]. For the disintegration reaction which is a five-body scattering problem consisting of an antiproton, three positrons, and an electron, we introduce a model potential to describe the interaction between an antihydrogen atom and leptons (electron and/or another positron) and adopt a model four-body calculation to calculate the formation cross section of the positronium antihydride and positronium positive ion [3]. The model potentials are optimized to reproduce the binding energy of antihydrogen positive ion and positronium antihydride.

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En route to a CPT test based on anti-H_2^+: vibrational spectroscopy of a H_2^+ ensemble and nondestructive spectroscopy of a single HD^+ ion in a Penning trap

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An attractive approach for testing CPT invariance is the comparison of a vibrational transition frequency of anti-H_2^+, composed of two antiprotons and a positron, with that of its matter counterpart H_2^+ [1,2].
The motivation for considering this - so far not existent - system is that its rovibrational transitions are intimately related to the presence of the antiproton-antiproton interaction, an interaction that can therefore be probed in the low-energy regime [3]. This regime is not accessible with high precision in other experiments. Furthermore, the transitions are strongly dependent on the ratio of positron mass and antiproton mass. In comparison, laser spectroscopy of antihydrogen has only a weak sensitivity to this ratio and antiproton Penning trap mass spectrometry experiments [4] face the challenge of progressing towards higher accuracy.
Due in part to (anti-)H2+ being both a molecule and an ion, its vibrational spectroscopy in a Penning trap [2] could exhibit several important advantages: need of only small particle numbers, access to

multiple candidate transitions, extremely high line quality factor, ultrasmall systematic shifts [5], long trapping times, possibility of nondestructive spectroscopy of a single anti-H_2^+ for extended duration.

Here we present progress in the exploration of techniques likely to be useful for future spectroscopy of anti-H_2^+. Evidently, we use matter systems for test purposes: H_2^+ and the related HD^+ molecular ion.

Concerning the spectroscopy of vibrational transitions in H_2^+, we report on the first laser vibrational spectroscopy [6], performed in a radiofrequency trap on small ensembles of sympathetically cooled H_2^+ molecules. We employed electric quadrupole spectroscopy [7], originally proposed by Dehmelt. Our spectroscopy was limited by Doppler broadening; we shall discuss our efforts towards Doppler-free spectroscopy.

Since the production rate of anti-H_2^+ is likely to be small, it could be essential to employ an "economic" spectroscopy technique: it should be non-destructive and should be able to work with a small number of particles or even a single particle. Using the ALPHATRAP Penning trap apparatus, we have succeeded in reliably confining and performing spectroscopy on one single HD^+ molecule for many weeks without interruption [8]. Electron spin resonance spectroscopy was performed on several transitions, allowing determination of the g-factor of the bound electron and the spin structure of the rovibrational ground level. The spectroscopy did not destroy the state, much less the molecule itself.

Finally, we have identified rovibrational transitions of H_2^+ or anti-H_2^+ having systematic Zeeman shifts in a Penning trap allowing for attractive levels of overall spectroscopic accuracy [2].

These results lead us to consider the next explorative step: implememting high-accuracy laser spectroscopy of H_2^+ in ALPHATRAP. The prospects will be outlined.

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Poster / **59**

Results from the Accelerators Validating Antimatter physics (AVA) network

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The 4M€ Accelerators Validating Antimatter physics (AVA) project has enabled an interdisciplinary and cross-sector R&D program on low energy antimatter research. The network comprised 13 universities, 9 national and international research centers and 13 partners from industry.

Between 2016 and 2021, AVA has successfully trained 16 early-stage researchers that were based at universities, research centers and companies across Europe where they carried out cutting edge research into low energy antimatter physics and related technologies.

This contributions presents the research and technology innovation highlights that came out of AVA. It also discusses the new approaches in researcher training and science communication realized by the network that were identified as best practice in Europe through formal reviews.

Parallel I / 60

Positronium Doppler laser cooling: results and perspectives

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Positronium is the bound state of an electron and its antimatter counterpart, a positron. With just two times the mass of the electron and no nucleus, this exotic compound is the lightest of all known atoms with no gluon contribution to its mass. Its electronic structure resembles the one of hydrogen with a factor two lower reduced mass. Positronium is therefore a system of particular interest for testing fundamental properties of antimatter such as the gravitational acceleration of antimatter in the Earth's gravitational field and bound state quantum electrodynamics. Positronium can also be used to form antihydrogen by collision with antiprotons [1]. All these experiments benefit from cold sources of positronium for example to remove the second order Doppler shift and transit time broadening in $1^3S \longrightarrow 2^3S$ spectroscopy or to increase the production rate of antihydrogen. However, laser cooling positronium poses a unique combination of challenges. First, the initial velocity distribution of thermalized positronium induces Doppler broadening of several hundreds of GHz. Being composed of two fundamental particles which can annihilate together, the lifetime of positronium is limited. In the ground ortho-state configuration, the annihilation lifetime of positronium is 142 ns setting the timescale available for laser cooling. The $1^3S \longrightarrow 2^3P$ transition used for laser cooling lies in the ultraviolet range (243 nm).
Here we report on the first experimental positronium laser cooling with broadband 70 ns long pulses [2]. We will report on the alexandrite laser system developed to overcome the challenges posed by positronium laser cooling as well as on the experimental results showing a reduction of temperature from 380(20)K to 170(20)K within 70 ns measured by two-photon resonant ionization on the Doppler sensitive $1^3S \longrightarrow 3^3P$ transition monitored by Positron Annihilation Lifetime Spectroscopy. Our results demonstrate that we realized the maximum of cooling efficiency allowed by classical Doppler cooling and that the transient excitation of positronium in the long-lived 2^3P state allows to extend the overall lifetime of the atoms. Finally, we will present future perspectives opened by this work and discuss the possibility to perform coherent laser cooling on positronium to reach even lower temperatures.

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Antimatter-Nucleus reactions with the Liège IntraNuclear Cascade (INCL) code

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The INCL intranuclear cascade code has been developed and used for a long time. Its aim is to simulate the interactions of light projectiles with all types of nuclei in an energy range from a few tens of MeV to 10-20 GeV. To do this, it has to be combined with a de-excitation code, and most of the time it is the ABLA code that is used. Both codes are also available in the Geant4 particle transport code. In addition, different versions of INCL are available in other codes (e.g. Phits, Genie).
The latest innovation in INCL is the ability to simulate antiproton-nucleus reactions, from at-rest to around 10 GeV. This is the subject that will be presented here, along with the way in which the implementations were made (hypotheses, ingredients) and the results that were obtained (comparisons with experimental data, and sometimes with other models). As the antineutron is currently being implemented, this subject could also be addressed. The next step will be to extend this to anti-deuterons, anti-tritons, etc.

Poster / 67

Formation of moving exotic muonium atoms during channeling of antimuons in carbon nanotubes under external electromagnetic radiation

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The paper proposes obtaining exotic moving muonium atoms Mu through the capture of valence electrons from carbon atoms by antimuons μ^+channeled (the channeling effect is described, for example, in [1]) along the axes of carbon nanotubes (CNTs). The probability of such captures, as in previous works [2,3], is calculated using non-stationary perturbation theory. However, in [2, 3], exotic atoms arose due to internal interactions, but in this study, the calculations are conducted under the conditions of resonant interaction with external electromagnetic waves acting on the channeled particles. We assume that this monochromatic wave has a frequency ω, is described by the vector-potential $\vec{A}(\vec{r},t)$, and propagates along the axis of the CNTs. Physically, this process can be represented as follows. Under the influence of an electromagnetic field, a valence electron from the state described, for example, in [4], leaves the carbon atom (ionization occurs) and is captured into one of the s-states of the Coulomb spectrum of the antimuon. In this case, the motion of the antimuon in the CNT channel is free along the z-axis with a longitudinal momentum $p_z = \mu_+ v$ and quantized in the transverse degrees of freedom. The probability of such capture under the influence of a perturbation $\hat{W}(\vec{r},t) = -\frac{i\hbar e}{\mu c}\vec{A}(\vec{r},t)\cdot\nabla$ in this work is calculated in the first approximation analogously to the calculations performed in the study of the photoelectric effect (see, for example, [5]).

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Parallel I / 69

Formation of light (anti)deuteron from a coalescence afterburner

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The advent of the LHC as \textit{antimatter factory} has enabled an unprecedented effort to measure the production of light (anti)nuclei from pp to heavy-ion collisions, providing input for a detailed study of nucleosynthesis in high-energy interactions. However, the production of these bound states is not modelled in commonly used event generators. Yet the detection of cosmic antinuclei is predicted to be a smoking gun of dark matter. To fill this gap, we developed a coalescence afterburner to be used with Monte Carlo generator inputs to model the production of light (anti)nuclei in hadronic interactions on an event-by-event basis.
In this work, event generators such as PYTHIA8.3, tuned to describe (anti)proton yields as measured at the LHC, are used as input to a Wigner function-based coalescence afterburner that forms a nucleus when two or more nucleons are close in phase space, depending on the momentum distribution of the nucleons, the nucleus wave function, and the size of the nucleon emitting source. The results are discussed in comparison to ALICE data and from the perspective of applying the model to estimate the fluxes of cosmic antinuclei for indirect dark matter searches with spaceborne experiments like AMS and GAPS.

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Prospects for Positronium Bose-Einstein Condensation

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Positronium (Ps), the bound state of an electron and its antiparticle positron, serves as a good probe for fundamental physics. As the lightest purely leptonic atom containing an antiparticle, Ps offers unique opportunities for precision tests of bound-state quantum electrodynamics (QED) and investigations into matter-antimatter asymmetry—the mystery underlying our matter-dominated Universe.

One of the long-standing goals in Ps research is the realization of Bose-Einstein Condensation (BEC) of Ps (Ps-BEC). Given its low mass, Ps stands out as an excellent candidate for achieving the first BEC containing antiparticles. Ps-BEC would allow us to study gravitational effects on antiparticles (specifically positrons) through interferometer experiments [1]. Additionally, it holds interesting potential for creating a 511-keV gamma-ray laser [2].

The challenge in achieving Ps-BEC is to satisfy stringent conditions: a high number density (on the order of 10^{18} cm^{-3}) and ultra-cold temperatures (below 10 K) within the short Ps annihilation lifetime of 142 ns. In this presentation, I will introduce the physics of Ps-BEC and provide an overview of our recent progress and future developments in creating dense and cold Ps using a recently proposed method [3].

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Hyperon puzzle of neutron stars examined from heavy-ion collisions and hypernuclei

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The hyperon puzzle of neutron stars refers to the problem that most of the equations of state with hyperons are not sufficiently stiff to support the observed massive neutron stars. One promising solution to the puzzle is that the three-body interaction between hyperon and medium nucleons produces so strong repulsion that Λ's do not appear in neutron stars. The Λ potential in nuclear matter which fulfills the Λ-suppressing scenario is calculated by using chiral effective field theory with a decuplet saturation model [1]. This Λ potential is highly repulsive compared to the conventional ones, and it should verified its consistency with existing experimental data.

We found that the repulsive Λ potential derived from chiral effective field theory is consistent with the Λ directed flow of heavy-ion collision [2] and the Λ hypernuclear spectroscopy [3]. On the other hand, the conventional attractive Λ potential is found to explain both the Λ directed flow and the Λ binding energy data at the same level of accuracy. In this talk, we will discuss what is needed to distinguish the repulsive and attractive Λ potentials from experimental data.

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Poster / **72**

Design and developing status of the data acquisition and the slow control systems in the M2e experiment at Fermilab

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The Mu2e experiment at Fermilab aims to observe coherent neutrinoless conversion of a muon to an electron in the field of an aluminum nucleus, with a sensitivity improvement of 10,000 times over current limits.
The Mu2e Trigger and Data Acquisition System (TDAQ) uses \emph{otsdaq} framework as the online Data Acquisition System (DAQ) solution.
Developed at Fermilab, \emph{otsdaq} integrates several framework components, an \emph{artdaq}

based DAQ, an \emph{art} based event processing, and an EPICS-based detector control system (DCS), and provides a uniform multi-user interface to its components through a web browser.
The Mu2e tracker and calorimeter data streams are processed by a one-level software trigger implemented within the \emph{art} framework.
Events accepted by the trigger have their data combined, post-trigger, with the separately read-out data from the Mu2e Cosmic Ray Veto system.
The Mu2e DCS is built on EPICS (Experimental Physics and Industrial Control System), an open-source platform for monitoring, controlling, alarming, and archiving.
A prototype of the TDAQ and DCS systems has been built and tested over the last three years at Fermilab's Feynman Computing Center. Now, the production system installation is underway.
This report covers our project's development progress, especially the web-based user interface, and slow control implementation.

Parallel I / **73**

Laser spectroscopy of the ground-state hyperfine splitting in muonic hydrogen

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Laser spectroscopy of muonic hydrogen (μp) is an ideal platform to probe the proton structure. At the Paul Scherrer Institute, the CREMA collaboration aims to measure the ground-state hyperfine splitting (1S-HFS) with a relative accuracy of 10^{-6} to infer the proton structure contribution (two photon exchange correction) with a relative accuracy of 10^{-4}. This opens the way for testing the hyperfine splitting in regular hydrogen down to the 10^{-8}–10^{-9} level, which could reveal potential BSM effects.
In this talk, I will explain the measurement principle and the present state of our experiment.

Poster / **74**

Muonic atoms reveal the structure of deformed nuclei

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Keywords: muonic atoms; nuclear structure; hyperfine structure

The study of exotic atoms, such as muonic hydrogen-like ions [1-3], provides an intriguing way to probe the internal structure of their atomic nuclei. In this work, we use nuclear structure simulations to accurately calculate the hyperfine splitting of muonic hydrogen-like ions, focusing in particular on the incorporation of finite volume corrections, such as Bohr-Weisskopf and Breit-Rosenthal, due to the penetration of the muon wavefunction into the nuclear electric charge and magnetic dipole densities [3-5]. These corrections are essential for refining our understanding of the nuclear magnetic and quadrupole moments.

The simulations leverage a modified Skyrme-Hartree-Fock-based model integrated with Bardeen-Cooper-Schrieffer (BCS) and Hartree-Two-Delta-Approximation (HTDA) corrections. This model is particularly effective in representing highly deformed nuclei [6] and focuses extensively on the isotopes $^{161,163}Dy^{65+}$ and other lanthanides, including $^{159}Tb^{64+}$. Additionally, this model is coupled with an adapted Dirac-Fock method for computing the muonic wavefunction within the derived nuclear magnetic and electric potential. The methodology is scalable and can be extended to multi-electron ions by analyzing the hyperfine anomaly across various isotopes.

Our findings reveal that while the discrepancy in hyperfine constants between two given finite size models is modest (approximately 1%) for both electronic and muonic penetrative wavefunctions, $s^{1/2}$ and $p^{1/2}$, the proximity of the muon to the nucleus results in an amplification of the absolute difference by two orders of magnitude (approximately $\times 100$), thus facilitating a more precise discrimination between theoretical models.

Our study aims to align theoretical predictions of muonic hydrogen-like ions with experimental data to validate our models and verify fundamental nuclear physics principles. This crucial comparative analysis not only tests the accuracy of nuclear structure predictions but also confirms the utility of muonic ions as effective nuclear probes. Moreover, the approach can be generalized across various nuclear models, serving as a benchmark for further investigations. The anticipated outcomes of this research will significantly enhance our understanding of the deformation and complex structures of lanthanides, thereby advancing the broader field of nuclear physics and refining theoretical frameworks for describing exotic atoms and highly deformed nuclei.

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Poster / **75**

Prospects from a cold antideuteron beam in AD/ELENA

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The generation of low-energy anti-nuclei for experimentation is a formidable challenge, stemming from the difficulty of primarily producing anti-nuclei in more than minuscule quantities during high-energy collisions. A notable exception is the antideuteron, for which several production mechanisms are known with a variety of efficiencies (from 0.1 to 10-5) and momentum/energy distributions. This presentation explores the perspectives offered by a low-energy antideuteron beam in advancing antimatter physics and assesses its technical feasibility, with a special focus on utilizing the capabilities of the existing AD/ELENA infrastructure.

Parallel I / 76

Synthesis of highly charged nuclear fragments in a Penning-Malmberg trap using antiprotons

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The Antimatter Experiment: Gravity, Interferometry, Spectroscopy (AEgIS) at CERN's Antimatter Decelerator (AD) is used for the production and study of antimatter bound systems, such as antihydrogen for the gravitational influence on a horizontal beam of cold antihydrogen atoms 1. AEGIS has achieved remarkable performance in trapping antiprotons and successfully demonstrated the

pulsed production of Rydberg excited antihydrogen [2,3]. The production process of antihydrogen is achieved through a charge-exchange reaction using laser-excited Rydberg positronium interacting with cold antiprotons stored within a Penning-Malmberg trap.
This technique is currently being adapted for the controlled formation of antiprotonic atoms containing medium-heavy nuclei [4]. So far, antiprotonic atoms were formed in beam-on-target experiments, primarily focusing on light systems such as antiprotonic helium [5,6]. Using the charge-exchange procedure developed for antihydrogen production, antiprotonic atoms can be selectively formed in highly excited Rydberg states inside a trapping environment, enabling precision laser spectroscopy of these systems. The relaxation of the bound antiproton leads to Auger electron and x-ray photon emission, eventually forming a fully or nearly stripped nucleus with the bound antiproton. The subsequent annihilation on the nucleus will result in the formation of highly charged nuclear fragments with a loss of one of more nucleons, these fragments can be captured within a nested trap when the recoil energy is sufficiently low. The rapid capture of the highly charged nuclear fragments opens the avenues for new applications and nuclear structure studies of the synthesized fragments [7].
Recent, experiments at AEgIS have successfully demonstrated the trapping of highly charged ions resulting from antiprotons annihilating with residual nitrogen gas in the cryogenic trap. These highly charged ions were further manipulated and could be identified using time-of-flight spectroscopy. This new advancement open up new possibilities for experiments probing the annihilation mechanisms, allowing further nuclear structure studies of the resulting fragments directly within the trap.

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Parallel I / **77**

Towards (anti)hydrogen fountains and interferometers with the HAICU project

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Precision comparisons of atomic hydrogen and its antimatter counterpart, antihydrogen, provide stringent tests of fundamental symmetries between matter and antimatter such as CPT invariance and the Weak Equivalence Principle. The most precise measurements of atomic hydrogen properties have traditionally been performed in atomic beams. In contrast, precision measurements of antihydrogen to date have been conducted within a magnetic trap environment, where experimental challenges arise due to the presence of an inhomogeneous field.

To significantly enhance the discovery potential with antihydrogen measurements, we have initiated an ambitious R&D project known as HAICU (Hydrogen-Antihydrogen Infrastructure at Canadian Universities). Located at TRIUMF—Canada's Particle Accelerator Centre in Vancouver—HAICU is utilizing atomic hydrogen to develop the techniques necessary for realizing atomic fountains and interferometers for antimatter. This, in turn, may provide opportunities for novel measurements on hydrogen itself, as no atomic fountains have ever been built for hydrogen.

This talk will provide an overview of the HAICU project, detailing our current progress and discussing the future potential for fountains and interferometers for both hydrogen and antihydrogen.

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Frequency metrology with antimatter

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According to the fundamental symmetries that underpin the Standard Model, both matter and antimatter should have been produced in equal quantities at the Big Bang. The absence of antimatter in our Universe as we observe it today, strongly motivates direct matter-antimatter comparisons, where any observed difference would lead to new physics. The Antihydrogen Laser Physics Apparatus (ALPHA) collaboration at CERN produces and traps antihydrogen atoms by combining antiproton and positron plasmas, which are subsequently used for precise studies. Recent progress includes the accumulation of thousands of atoms, direct laser cooling of the antihydrogen sample 1 and the first observation of the motion of antihydrogen in a gravitational field [2].

Laser spectroscopy of antihydrogen has already resulted in a test of CPT symmetry to a relative precision of 2 × 10−12 [4]. In hydrogen however, the same spectral feature, the 1S-2S transition, has been determined up to a precision of 4 × 10−15 [5]. To enable matter-antimatter comparisons at that level, we have implemented a Cs fountain clock in collaboration with NPL [3]. The fountain acts as a local absolute frequency reference
and is used to steer an active hydrogen maser in the same laboratory. In addition to comparing the frequency of the maser with our fountain, we also cross-check against national metrology labs via satellite frequency transfers. A frequency comb and a stabilized fiber link, as well as two ultra-low expansion cavities, then allow for accurate determination of the laser frequency that is experienced by the antihydrogen atoms.

I will present recent progress and the current status towards a more precise comparison of the 1S2S transition in hydrogen and antihydrogen. I will also detail how we plan to access fundamental quantities, such as the Rydberg constant in an antimatter system and the antiproton radius, by carrying out laser spectroscopy on higher-lying excited states in antihydrogen.

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Demonstration of one-dimensional chirp cooling of positronium to ultra-low temperatures

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Positronium (Ps), an exotic atom composed of an electron and its antiparticle, the positron, serves as an excellent system for fundamental physics investigations. Its unique composition of light leptons makes it an ideal system for testing Quantum Electrodynamics (QED) and probing physics beyond

the Standard Model. A key aspect of such studies involves comparing calculated energy intervals with precise measurements, often achieved through laser spectroscopy. Because of the current situation that measured precision is inferior to that of theory, breakthroughs on experimental side are required; one of which is Ps cooling for both precision and accuracy.
In the presentation, we will report the demonstration of one-dimensional chirp cooling of Ps 1. By subjecting Ps to an optimized laser system developed in our laboratory [2], we achieved an unprecedentedly low temperature of approximately 1 K. This temperature is two orders of magnitude colder than what conventional cooling methods can achieve. The laser system was designed to maximize the number of Ps atoms with zero velocity along the cooling axis. Numerical simulations, rigorously modeling the Ps-laser interaction, allowed us to reasonably reproduce the resulting velocity distribution after laser cooling. We will also discuss about improvements for cooling the majority of Ps atoms thermally emitted [3], three-dimensional laser cooling, and prospects for precision spectroscopy powered by laser-cooled Ps.

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Poster / 80

A novel platform for antiprotonic atom research using Paul and Penning-Malmberg traps

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AEgIS experiment at CERN utilizes a charge-exchange reaction with Rydberg positronium for the formation of a pulsed antihydrogen (Hbar) beam for a gravity measurement in the absence of external fields 1. Hbar formation with all its intermittent steps is achieved in cryogenic, Ultra High Vacuum conditions, inside of a Penning-Malmberg trap system.

The controlled environment of the AEgIS Penning-Malmberg trap can be used for synthesis of other exotic systems, as well as direct and precise observations of matter-antimatter interactions. In particular, formation of Rydberg antiprotonic atoms inside the traps has been proposed in recent years [2]. In fact, the same charge exchange reaction used by AEgIS for Hbar can be used for substituting an electron with an antiproton on a Rydberg orbit of a heavy ion. The antiproton would then cascade down while the atom undergoes a series of radiative and non radiative transitions to be inevitably destroyed when it reaches the atomic nucleus [3]. Controlled creation of such an antiproton-bound atom in cryogenic trap conditions would would allow recording of the full spectrum of the antiprotonic transitions, measurements of antiproton annihilations on the nucleus and production of nuclear fragments. Eventually, the technique can pave way to novel isotope formation, selective proton/neutron removal, controlled reconstitution of the electron orbitals of depleted nuclei, novel material synthesis by combining nuclear fragments with (partially) reconstituted electron orbitals - e.g. femtotechnology.

As mentioned, the trapping charge exchange reactions of antimatter have to be conducted in the cryogenic UHV conditions of the Penning-Malmbeg trap. Recently, trapping and manipulation of ions has been tested within the AEgIS apparatus with encouraging results. However, most measurements on (Highly Charged) Ions are done in Paul traps, in warm vacuum setting that allow access of extended experimental infrastructure. We have undertaken to build a Paul trap-based ion source, as well as ion beam delivery line in order to provide the AEgIS experiment with controlled pulses of (negative or positive) ions that can be co-trapped with antiprotons (and electrons) for antimatter-matter precision experiments. On the other hand, we are preparing the extraction region of the AEgIS apparatus to host an array of traps, laser and detector systems for collection and manipulation of the highly charged products of the reactions performed in the controlled cryogenic environment. The design of the extraction line is modular, flexible, allowing for constant additions and modifications, transforming the AEgIS experiment into a platform for new particle, nuclear and material physics.

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Poster / 81

The ground state hyperfine splitting in muonic hydrogen (Hyper-mu) experiment at PSI

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The Hyper-mu experiment at PSI aims at the first measurement of the ground state hyperfine splitting in muonic hydrogen (μp) with an accuracy of 1 ppm. Such a measurement would lead to the extraction of the two photon exchange, encoding the proton Zemach radius and polarizability, with an unprecedented relative uncertainty.

Toward the measurement of the ground state hyperfine splitting in μp, we develop a unique pulsed laser system with the aim of delivering 5mJ pulses at a wavelength of 6.8 μm randomly triggered on the detection of muons. We report on the latest laser development within the experiment, the several developments of the detection system that was carried out and the optimization of the experimental parameters to obtain a successful resonance signal.

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The PANDA Experiment

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The PANDA experiment represents one of the scientific pillars of the Facility for Antiproton and Ion Research by utilizing an antiproton beam for unsurpassed high statistics and high precision hadron physics in the meson and baryon sector with flavors up to charm. The PANDA experiment will use a multipurpose magnetic detector with full particle ID comprising a target and a forward spectrometer to make maximum us of the stored antiproton beam with momenta up to 15 GeV/c and luminosities reaching 10^32/cm2/s when impinging on a our world record gas-jet target.

The current status of PANDA will be presented as well as bridging activities which will allow scientific harvest with PANDA technologies and along the lines of the scientific goals of PANDA as long as the PANDA detector is not fully operational.

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Antihydrogen production and beam formation for hyperfine spectroscopy at low magnetic field

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The ground state hyperfine splitting was recently measured to 0.4 ppb for a beam of hydrogen in the ASACUSA spectrometry line (Nowak 2024). We plan to repeat the experiment using an antihydrogen beam. So far (Kuroda 2014, Kolbinger 2021), the beam intensity is too low (<1 ground state atom per cycle) to distinguish signal from background. In an upgraded mixing trap, we cool up to 4x10ˆ7 particles to T˜25 K (Amsler 2022)– five times lower than before. Using a positron-antiproton mixing scheme similar to ALPHA's (Ahmadi 2017), we produce 4x10ˆ5 antihydrogen atoms—seven times more than previously reported—all of which annihilate without forming a beam. A new method of mixing (Jonsell 2019) will soon be applied to increase the beam-like fraction. First results may be available by the time of this conference.

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Welcome

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Kaonic bound states

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SIDDHARTA 2 - first results

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Theory of kaon-nucleon interaction

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Antiproton and antineutron formfactors @ BES3

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Cosmic anti-deuteron flux from exotic sources

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Measurement of anti-3He nuclei absorption in matter and impact on their propagation in the Galaxy

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AMS - antimatter in the universe

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Antiprotonic helium

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X-rays of muonic and antiprotonic atoms

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Physics with Antiprotons and Antihydrogen - theory overview

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Lorentz Violation, CPT violation, and Spectroscopy Experiments

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Test of CPT and Lorentz invariance with a cold (anti)hydrogen beam

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Lorentz violation test with pulsed Ramsey spectroscopy with Yb+

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Pontecorvo process

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Antiproton annihilation on nuclei

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Probing the size and binding energy of the hypertriton in heavy ion collisions

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Observation of antimatter hyperhydrogen-4 at STAR

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Tetraquarks

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PSI - future plans, extensions

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Discussion - FuPhy

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Poster / 111

Ultracold neutron sources for fundamental physics —status at TRIUMF and future prospects

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Ultracold neutrons (UCNs), neutrons with kinetic energies of ⊠ 300 neV, have the unique property of being stored in a vessel with an appropriate surface material for a time on the order of 100 s, and have been used for key experiments in fundamental physics. Originally, very cold neutrons were mechanically decelerated to obtain UCNs. In 1977, the so called super-thermal method was proposed, which utilizes the inelastic scattering of neutrons in a medium and enables a high UCN density in the source 1.
The TUCAN (TRIUMF Ultracold Advanced Neutron) collaboration has developed an accelerator-driven super-thermal UCN source using superfluid helium as a convertor. The key components of the UCN source, including high-performance helium and liquid deuterium cryostats, have been developed through a joint effort between Japanese and Canadian institutes. [2, 3]. The UCN source is currently undergoing commissioning in preparation for the first beam test at TRIUMF. In parallel, In parallel, a spectrometer was developed to measure neutron electric dipole moment (EDM) [4]. It is anticipated that the intense source will provide UCNs sufficient for two-orders-of-magnitude improved statistics of neutron EDM measurements over previous experiments. Recently, a decision was made to build a new research reactor in Fukui, Japan [5]. Based on technologies developed through the TUCAN source, a helium-based super-thermal UCN source is planned to be built in this future facility. Ideas for experiments using this UCN source are currently being sought; one of which is to search for the neutron-antineutron oscillation with UCNs.
In this paper presentation, I will present the principle of super thermal UCN sources, report the status of the TUCAN source at TRIUMF, and discuss the potential of the future source in Fukui.

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PSI - future plans, extensions

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At the Paul Scherrer Institut (PSI) muon rates of up to 4x10ˆ8 mu/s are available, produced by its 1.4 MW proton accelerator complex HIPA. While these are currently the highest muon rates available worldwide, projects in the US and Japan are underway that will be able to surpass these intensities by several orders of magnitude.
In order to maintain PSI's position at the intensity frontier in muon physics and to utilize the unique DC machine structure, a project is under way of creating a next-generation high-intensity muon beam (HIMB) by modifying the existing Target M station. Surface muon rates of the order of 10ˆ10 mu+/s can be achieved by placing two normal-conducting capture solenoids close to a slanted slab target and transporting the muons to the experimental areas with a beamline consisting of large aperture solenoids and dipoles.
This contribution will present the current status of the project.

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Lorentz Violation, CPT violation, and Spectroscopy Experiments

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This presentation outlines a model derived from the Standard-Model Extension for testing Lorentz symmetry in atomic spectroscopy experiments and examines potential signals for Lorentz violation accessible in these experiments. These signals include CPT violation, indicated by differences between the hydrogen and antihydrogen spectra, as well as sidereal and annual variations of observables. Additionally, the talk reviews the progress made in constraining the SME coefficients within the model and offers suggestions for future enhancements in this research area.

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Measurement of anti-3He nuclei absorption in matter and impact on their propagation in the Galaxy

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Some dark matter candidates, such as the Weakly Interacting Massive Particles (WIMPs), are expected to annihilate in our galaxy and produce, among other particles, light antinuclei, which can be observed as cosmic rays. However, the same antinuclei can also be produced in ordinary cosmic ray collisions with the interstellar gas. Thus, precise modelling of signal and background cosmic ray fluxes, including the inelastic losses in the interstellar medium, is required to draw conclusions from future measurements expected by the AMS and GAPS experiments.
Recently, measurements of the momentum-dependent inelastic cross sections of antideuterons and antihelium-3 nuclei were carried out employing the ALICE detector material as a target. The antihelium-3 inelastic cross sections have been obtained by applying the antimatter to-matter ratio and TOF-to-TPC matching methods in pp and Pb-Pb collisions, respectively. These, for the first time, measured inelastic cross sections have been implemented in the GALPROP propagation model to estimate the losses in the antihelium-3 cosmic ray fluxes due to inelastic interactions with the interstellar medium.
The results of this interdisciplinary study by ALICE allowed the determination of the transparency of our galaxy to the propagation of the antihelium-3 from dark matter annihilation and ordinary cosmic ray collisions, and to demonstrate that antihelium-3 nuclei are a promising probe for indirect dark matter searches.

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PUMA - Probing the surface of atomic nuclei with antiprotons

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The main goal of the PUMA 1 (antiProton Unstable Matter Annihilation) experiment is to use antiprotons as a tool to investigate the matter density of short-lived nuclei. For this, antiprotons produced at the Antiproton Decelerator (AD) facility at CERN and decelerated by the Extra Low Energy Antiproton storage ring (ELENA) will be captured, cooled and transported to the ISODLE facility at CERN where the antiprotons will be mixed with short lived isotopes. During this process, an antiproton can be captured by the nucleus and will subsequently annihilate with a neutron or a proton at the surface of the nucleus itself. The pionic fingerprint of this annihilation will be measured using a time-projection-chamber. With this knowledge, the ratio of protons to neutrons on the outermost part of the nuclei distribution can be determined and phenomena like neutron or proton halos or neutron or proton skins can be investigated.
An overview of the PUMA experiment will be given, the current status will be discussed and some of the main physics goals will be highlighted.

1 Aumann et al., Eur. Phys. J. A (2022) 58: 88

Poster / **116**

Towards a Rydberg Interferometer to test the Weak Equivalence Principle with Positronium

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The current theory of General Relativity is based on the Weak Equivalence Principle (WEP), which states that the inertial and gravitational mass are equivalent. Tests of the WEP with matter have resulted in its confirmation to a relative precision of 10-15 1, but there have been hardly any results from experiments involving antimatter. A difference in the gravitational behaviour of matter and antimatter might help to explain the observed abundance of matter in the universe.
We propose an interferometry experiment using Positronium (Ps), the bound state of an electron and its antiparticle - the positron. The short lifetime of the ground-state Ps of 142 ns complicates an interferometry experiment, but this can be circumvented by the excitation to a high Rydberg state, which results in the suppression of annihilation and an increase in the lifetime to tens of µs [2]. The proposed interferometer is an electrical analogue of a Stern-Gerlach experiment; a superposition of Rydberg states with differing static electric dipole moments is allowed to evolve in electric field regions and acquire a measurable phase difference, depending on the interaction of the atomic states with the fields under gravity.
Unlike antihydrogen, Ps is a purely leptonic system, hence it is not influenced by possible effects of the binding energy of quarks on the gravitational behaviour [3]. This makes it a complementary measurement to the ongoing work with antihydrogen at CERN [4].
In the initial stage we will build a proof-of-principle setup with Helium which will afterwards be adapted to Ps. In this poster we will present the measurement technique along considerations on the experimental realisation and possible limitations.

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Discussion - FuPhy

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Improved bounds on Lorentz violation from long-coherence Ramsey spectroscopy in Yb+

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High precision spectroscopic measurements in trapped cold ions, have enabled various sensitive searches for new physics beyond the Standard Model 1. Local Lorentz invariance (LLI) is suggested to be violated in extensions of the Standard Model that include quantum-gravity [2]. We here report on a stringent test of local Lorentz invariance (LLI) in the electron-photon sector based on a novel radiofrequency (rf) composite pulse Ramsey method in the meta-stable 2F7/2 manifold of the Yb+ ion [2]. The method extends the coherence time to several seconds and uses the most sensitive magnetic sub-levels of the F state to Lorentz violation [4]. As a result, improved bounds on Lorentz violation were extracted in ten times less averaging time. As an outlook, we will discuss the progress in extending this method to multiple ions and elaborate on plans to further explore entangled decoherence-free states for various searches for new physics.

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Prospect of hadronic-molecule with strangeness

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Recently, we conducted a kaonic nuclear-bound state search experiment using a K^- beam (1 GeV/c) bombarding a ^{3}He target. We succeeded in observing a kaonic nuclear quasi-bound state, "K^-pp", via a nucleon knockout reaction, $K^-N \to \overline{K}n'$, followed by the decay $\overline{K}NN \to \Lambda p(2N_{\overline{K}A})$ in the two-nucleon $\overline{K}$ absorption process, resulting in the final state $\Lambda p + n'$. The result shows that

the “K^-pp” binding energy is about 40 MeV below the binding threshold, with a decay width of about 100 MeV. From the Λp decay, the isospin of the system is determined to be $I_{\overline{K}NN} = 1/2$. The momentum transfer distribution of the Λp system is very broad, implying that the size of the “K^-pp” system might be very compact [1, 2].

We extended our study on the kaonic nuclear-bound state in two ways: A) by studying the mesonic decay process of the $\overline{K}NN$ via one-nucleon $\overline{K}$ absorption ($1N_{\overline{K}A}$: $\overline{K}N \rightarrow \pi Y$), and B) by searching for the $\overline{K}NNN$ bound state through the Λd invariant mass study of the $\Lambda d + n'$ final state with a k^- beam (1 GeV/c) bombarding a ^{4}He target. The aim of A) is to understand why the decay width of “K^-pp” is about twice as broad as that of $\Lambda(1405)$ (≈ 50 MeV), which is assumed to be a molecule-like hadronic cluster composed of a $\overline{K}$ meson and a nucleon, i.e., $\Lambda(1405) \equiv \overline{K}N$, as introduced by R. H. Dalitz et. al. [3]. The result shows that the $\overline{K}NN \rightarrow \pi YN$ decay is dominant ($1N_{\overline{K}A} \gg 2N_{\overline{K}A}$) and that the $\pi\Sigma N$ to $\pi\Lambda N$ ratio is about 1:1, indicating that the $I_{\overline{K}N} = 1$ absorption channel is approximately equal to the $I_{\overline{K}N} = 0$ channel. The result also suggests that there is a hint of the “$\overline{K}^0nn$” bound state, a charge mirror state of “K^-pp”, existing in the $\pi^-\Lambda p$ invariant mass spectrum of the $\pi^-\Lambda p + p'$ final state.

In the Λd invariant mass study B), the two dimensional preliminary spectrum of the Λd invariant mass and the momentum transfer to Λd ($m_{\Lambda d}, q_{\Lambda d}$) shows an almost identical distribution to ($m_{\Lambda p}, q_{\Lambda p}$), indicating the presence of $\overline{K}NNN$, decaying to Λd. If this is another kaonic nuclear-bound state, then the isospin, spin parity is fixed to be $I(J^P) = 0(1/2^-)$.

In this talk, we’ll describe these two new results on kaonic nuclear-bound states and discuss the prospects of studying the molecule-like hadronic cluster with strangeness.

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Poster / **120**

Rabi-oscillation spectroscopy : high precision time-domain analysis applied to muonium hyperfine resonance

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Muonium (Mu), an exotic atom composed of a positive muon and an electron (μ^+e^-), is a suitable probe for precise tests of bound-state QED as well as for searching for new physics beyond the Standard Model. MuSEUM collaboration at J-PARC has so far succeeded in measuring the ground-state hyperfine splitting (HFS) of the muonium atom under the zero magnetic field, and is now aiming at a precision of 2 ppb under strong magnetic fields to determine the magnetic moment and the mass of the muon.
We have developed a new spectroscopic technique named “Rabi-oscillation spectroscopy”, in which the resonance frequency can be determined directly from the time evolution of the Rabi oscillation at a fixed frequency of the applied electromagnetic wave (i.e. microwave or laser). In contrast to standard spectroscopy, this new technique does not require any frequency scanning, any drawing of resonance curves nor any Fourier transform in the analysis.

Rabi-oscillation spectroscopy has not only found application to our HFS microwave resonance studies of muonium 1 and muonic helium (μ^-He) atoms, but it can also be applied in principle to other exotic and ordinary atoms and molecules.

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Public Lecture

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Cosmic Antiparticles: Latest Results from the Alpha Magnetic Spectrometer on the International Space Station

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The Alpha Magnetic Spectrometer (AMS) is a precision particle physics detector on the International Space Station. Over 12 years, AMS has collected more than 230 billion cosmic rays, from elementary particles to iron nuclei, at energies up to multi-TeV. The precision spectrometer measures elementary particles and nuclei to ˜1% accuracy, yielding many surprising results. The latest AMS results will be presented with a particular emphasis on elementary particles and antiparticles (protons, electrons, positrons, and antiprotons). These data reveal unexpected properties in cosmic rays and indicate new sources of high-energy antiparticles. The AMS results continue to provide unique insights into understanding the origin of dark matter and antimatter, and exploring new physics phenomena in the cosmos.

Poster / **123**

Positron polarimetry with resonant microwave radiation

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Spin polarized positron beams are employed in investigations of magnetic and electronic structure dynamics [1, 2] and may also be useful in the production of a positronium Bose-Einstein condensate [3]. Slow positron beams derived from radioactive sources are naturally spin polarized due to the non-conservation of parity in the beta decay process [4] although measuring the polarization can be challenging. Existing polarimetry techniques involve either strong magnetic field (˜ 1 T) [5], high density beams (1016 cm-3) [6] or high beam energies (100 keV) [7]. Since the polarisation is conserved in positronium formation, a technique involving depletion of magnetic sub-levels of triplet positronium via irradiation by microwaves may be more desirable. In this work we describe such an approach where the spin polarisation of a positron beam is deduced from depletion of the asymmetric population of magnetic sub levels of a metastable positronium beam [8] using circularly polarised microwave radiation. We present the experimental method and recent progress of the investigation.

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Cosmic antinuclei from exotic sources

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Cosmic rays are messengers of distant Galactic places and times. Due to the baryon asymmetry of the Universe, antinuclei in cosmic rays inherently point to origins in baryon-symmetric high energy particle physics or very exotic places. This talk reviews sources of cosmic ray antinuclei −observed, plausible or possible− and the role that antinuclei may play in their detection.