Ulmer Fundamental Symmetries Laboratory
Chief Scientist: Stefan Ulmer (Dr. rer. nat.)

(0) Research field

CPR Subcommittee: Physics

Keywords: Antimatter / Penning Traps / Precision Tests / Fundamental Symmetries / Fundamental Constants

(1) Long-term goal of laboratory and research background

The Ulmer Fundamental Symmetries Laboratory is leading the BASE collaboration at the antiproton decelerator of CERN, Geneva, Switzerland. Our goal is to perform high-precision comparisons of the fundamental properties – such as magnetic moments and charge-to-mass ratios – of single protons and antiprotons in Penning traps. Our measurements provide stringent tests of CPT invariance, which is the most fundamental symmetry in the Standard Model of Particle Physics. To this end, we have developed the sophisticated Penning trap system BASE. With our experiments we have performed the most precise test of CPT invariance in the baryon-sector by comparing the antiproton-to-proton charge-to-mass ratio with a fractional precision of 69 parts in a trillion (p.p.t.), the most precise measurement of the proton magnetic moment with a fractional precision of 0.3 parts in a billion (p.p.b.), as well as the most precise measurement of the antiproton magnetic moment with a fractional precision of 1.5 ppb.

In addition to BASE, the Ulmer Fundamental Symmetries Laboratory is involved in the ASACUSA-CUSP experiment. Here we aim at a high precision measurement of the hyperfine structure of antihydrogen. In this experiment we succeeded in producing a beam of antihydrogen atoms, which is a major step towards the planned spectroscopy. Moreover, the Ulmer lab takes part in a Max-Planck/RIKEN collaboration to measure the mass of the proton in natural units, the PENTATRAP experiment for ultra-high-precision mass spectrometry, as well as an effort to measure the magnetic moment of the hellion ion $^3He^{2+}$.

(1) Research activities in FY2020

(A) Data Analysis of 2018/2019 Proton/Antiproton Charge-to-Mass Ratio Measurement Campaign

The laboratory has developed a considerably upgraded experimental apparatus and conducted a long term study of the proton-to-antiproton charge-to-mass ratio. Two years of data were taken, the dataset provides

1.) One of the best tests of CPT invariance in the baryon sector in which a fractional precision of 16 parts in a trillion was reached.
2.) The long term study enables constraining several time dependent phenomena mediated by exotic physics.
3.) The study contains data over more than a sidereal year and allows us to constrain antigravity effects in antimatter experiments

The high precision which was achieved in these experiments required extensive systematic studies and the invention of several new data analysis methods, which kept parts of the group busy for an entire year. A manuscript is currently under evaluation at Nature.

(B) Constraints on the coupling between axion-like dark matter and photons using an antiproton superconducting tuned detection circuit in a cryogenic Penning trap

We have used the superconducting detection systems used in the BASE antiproton experiments to search for the conversion of axions and axion-like particles into radiofrequency photons. By searching the noise spectrum of our fixed frequency resonant circuit for peaks caused by axion-to-photon conversion in the strong magnetic field of the Penning trap magnet, we are able to constrain the coupling of ALPs with masses around 2.7906-2.7914 neV to be $g_{ag}<1*10^{-11}$ / GeV. This is more than one order of magnitude lower than the best laboratory haloscope and approximately five times lower than the CAST helioscope, setting limits in a mass and coupling range thatis not constrained by astrophysical observations. This approach can be extended to many other Penning trap experiments, and has the potential to provide stringent high-resolution limits in the low ma range. Using the existing technologies available in BASE and developing a purpose-built experiment, the detection bandwidth could be increased by a factor of >1000 at about 200-fold improved detection sensitivity. The study was published in Physical Review Letters.

(C) Development of a High Bandwidth Cryogenic Single Particle Detector

We have developed a highly sensitive superconducting toroidal detection system with a quality factor of Q=140000 and tuneable resonance frequency, covering a frequency span between 350 kHz and 1 MHz. Frequency tuneability is provided by a purpose-built PTFE/Copper capacitor driven by a cryogenic movable piezoelectric stick-slip-stage. The quality factor of the developed device is for all tuned resonance frequencies higher than 100000, providing highest detection sensitivity in the entire covered frequency range. This new development is of considerable interest for both, advanced high-precision Penning trap experiments, as well as LC-circuit based haloscope-antennas setting stringent limits on the conversion of axion-like particles to radio-frequency photons. A manuscript is in preparation.

(D) Preparation of a New Antiproton Magnetic Moment Measurement Run

The preparation of a further upgrade of the experiment to tackle measurements of the antiproton magnetic moment with parts per trillion precision was one of the main project the group was dealing with. The new experiment features an upgraded advance Penning trap system, which includes a purpose-built cooling trap for fast selective resistive cooling cycles (one PhD student), a local magnetic tuning system (one PhD student) to tune the local magnetic field of the trap to lowest gradients, and an upgraded precision measurement trap. Both together will allow magnetic moment measurements at considerably improved fractional precision and at improved sampling statistics. The magnetic shimming system will moreover allow us to improve the resolution in systematic studies. In addition, a new interface to connect BASE to the new ELENA storage ring has been developed successfully (one Post-Doc). The experiment is ready to be cooled down and prepared for beam-operation within the 2021 antiproton run, with the clear perspective to improve the measurement of the antiproton magnetic moment to sup-parts-per-billion precision.

(E) Setup of the Transportable Antiproton Trap BASE-STEP

To further enhance measurements of the fundamental properties of protons and antiprotons, the antiprotons need to be transported out of the antiproton decelerator facility. The transportable trap is under development, a design study was completed, a new superconducting magnet has been ordered and the cryogenic trap experiment was developed. The device will be ready to take the antiproton beam in the 2022 antiproton run. The project is part of the Max Planck, RIKEN, PTB center for Time, Constants, and Fundamental Symmetries.

(F) Measurement of the Magnetic Moment of $^3He^+$

First discovered in 1934 and believed to be a radioactive isotope of ^4He, nowadays ^3He has become one of the most important candidates for studies in fundamental physics, nuclear and atomic structure, magnetometry and metrology as well as chemistryand medicine. Compared to ^4He the unpaired neutron in ^3He gives rise to a negative nuclear magnetic moment and thus a coupling of the nuclear spin with the electron spin in single charged $^3He^+$. We exploit this coupling in a novel measurement technique that enables us to precisely measure the nuclear and electron magnetic moment of ^3He as well as the zero-field hyperfine splitting. The nuclear g-factor of $^3He^+$ was measured with a relative precision of 1 ppb, allowing for the determination of the g-factor of the bare nucleus $gI = -4.2552507004(30)_{stat}(17)_{sys}$ via the accurate calculation of the diamagnetic shielding effect $\sigma(^3He^+) = 0.000\ 035\ 507\ 38(2)$. This constitutes an improvement of the precision by one order of magnitude compared to previous indirect determinations of this value and provides the first direct and stand-alone calibration of ^3He NMR probes. Data were analyzed a manuscript is under consideration at Nature.

(G) Sympathetic Cooling of Protons

Efficient cooling of trapped charged particles is essential to many fundamental physics experiments, high-precision metrology, and quantum technology. Until now, sympathetic cooling has required close-range Coulomb interactions although there is sustained desire to bring laser-cooling techniques to particles in macroscopically separated traps, extending quantum control techniques to previously inaccessible particles such as highly charged ions, molecular ions, and antimatter. We demonstrated sympathetic cooling of a single proton using laser cooled Be^{+} ions in spatially separated Penning traps. The traps are connected by a superconducting LC circuit that enables energy exchange over a distance of 9 cm. We simultaneously demonstrate the cooling of a resonant mode of a macroscopic LC circuit with laser-cooled ions and sympathetic cooling of an individually trapped proton, reaching temperatures far below the environment temperature. Importantly, as this technique uses only image-current interactions, it can be easily applied to an experiment with antiprotons, facilitating improved precision in matter-antimatter comparisons and dark matter searches. The experiment was conducted successfully, a manuscript was accepted for publication in Nature.

(H) Detection rf Metastable Exotic Long Lived Atomic States by Penning trap Mass Spectromety

In collaboration with the group of Klaus Blaum of the Max Planck Institute for Nuclear Physics (MPIK), Heidelberg, Germany, and within the Max Planck, RIKEN, PTB Center for Time, Constants and Fundamental Symmetries, RIKEN Fundamental Symmetries Laboratory contributed to a study, which reports on the observation of a long-lived metastable electronic state in a highly charged ion, by measuring the mass difference between the ground and excited states in rhenium. This measurement provides a non-destructive, direct determination of an electronic excitation energy of the exotic HCI-state. The result is in agreement with advanced calculations. The study was published in Nature.

(3) Members

(Chief Scientist)
Stefan Ulmer

(Special Postdoctoral Researcher)
Elisabeth Johanna Wursten

(Postdoctoral Researcher)
Barbara Maria Latacz

(PhD Students)
Markus Fleck (JRA fellow)
Stefan Erlewein (Gentner Fellow (CERN PhD))
Julia Jaeger (Max Planck PhD Position)

(Visiting Scientists)
Yasunori Yamazaki (senior emeritus)
Jack Alexander Devlin (CERN LD position)
Peter Micke (CERN fellow position)
Christian Smorra (ERC-PI position)

(4) Representative research achievements

1.) **Measurement of the Principal Quantum Number Distribution in a Beam of Antihydrogen Atoms**, B. Kolbinger et al. (ASACUSA collaboration), EPJD **75**, 91, (2021)
2.) **Detection of Metastable Electronic States by Penning Trap Mass Spectrometry**
R. X. Schüssler, H. Bekker,, M. Braß, H. Cakir, J. R. Crespo López-Urrutia, M. Door, P. Filianin, Z. Harman, M. W. Haverkort, W. J. Huang, P. Indelicato, C. H. Keitel, C. M. König, K. Kromer, M. Müller, Y. N. Novikov, A. Rischka, C. Schweiger, S. Sturm, S. Ulmer, S. Eliseev, K. Blaum
Nature **581**, 64 (2020)
3.) **Constraints on the coupling between axion-like dark matter and photons using an antiproton superconducting tuned detection circuit in a cryogenic Penning trap**
J. A. Devlin, M. J. Borchert, S. Erlewein, M. Fleck, J. A. Harrington, B. Latacz, J. Warncke, E. Wursten, M. A. Bohman, A. H. Mooser, C. Smorra, M. Wiesinger, C. Will, K. Blaum, Y. Matsuda, C. Ospelkaus, W. Quint, J. Walz, Y. Yamazaki, S. Ulmer, Phys. Rev. Lett. **126**, 041301, (2021).
4.) **Sympathetic cooling of a trapped proton mediated by an LC circuit**

M. A. Bohman, J. A. Devlin, M. J. Borchert, S. Erlewein, M. Fleck, J. A. Harrington, B. Latacz, J. Warncke, E. Wursten, A. H. Mooser, C. Smorra, M. Wiesinger, C. Will, K. Blaum, Y. Matsuda, C. Ospelkaus, W. Quint, J. Walz, Y. Yamazaki, S. Ulmer, Nature, accepted (2021).

(5) Invited Talks given in FY2020 (Stefan Ulmer talks, 12 additional talks by other members and associated members of the Ulmer group)

(1) **Application of Quantum Technologies at the Antiproton Decelerator of CERN**
Perspectives on Quantum Sensing and Computation for Particle Physics (07/2021)

(2) **Testing Fundamental Symmetries with Antiprotons and Protons in Penning Traps**
Virtual Marcel Grossmann Meeting (07/2021)

(3) **Feebly Interacting Particles at the Antimatter Factory of CERN**
FPC Meeting, CERN, Geneva, Switzerland (06/2021)

(4) **Testing CPT invariance in Penning Traps**
CPT-School, Indiana University, Bloomington, US (05/2021)

(5) **Search for Feebly Interacting Particles at the Antiproton Decelerator of CERN**
CERN Detector Seminar, CERN, Germany (04/2021)

(6) **Application of Quantum Technologies at the Antiproton Decelerator of CERN**
CERN Directorate Meeting, CERN, Germany (04/2021)

(7) **Studies of Exotic Physics with Antiprotons and Protons in Penning Traps**
Online Seminar at RIKEN (03/2021)

(8) **Testing Fundamental Symmetries and Exotic Physics in Penning Traps**
Seminar, Quantum Universe Cluster, Hamburg, Germany (03/2021)

(9) **Search for Feebly Interacting Particles at the Antiproton Decelerator of CERN**
Physics Beyond Colliders Meeting, CERN, Germany (02/2021)

(10) **BASE: Testing Exotic Physics with Single Trapped Antiprotons**
Official Seminar of the QUANTUM group at Univ. Mainz, Germany (02/2021)

(11) **Fundamental Physics in Penning Traps and Precision Traps**
School on Trapped Charged Particles, Les Houches, France (02/2021)

(12) **BASE Annual presentation 2020**
Meeting of the SPSC, CERN, Geneva, Switzerland, (01/2021).

(13) **BASE Collaboration Meeting 2021**
Meeting of the SPSC, CERN, Geneva, Switzerland, (01/2021).

(14) **Tests of Fundamental Symmetries with Single Particles in Penning Traps**
Seminar on Precision Physics and Fundamental Symmetries, (remote seminar 04/2020)

Laboratory Homepage
https://www.riken.jp/en/research/labs/chief/ulmer_unit/index.html
http://ulmerfsl.riken.jp/