High-precision measurements and searches for New Physics

766. WE-Heraeus-Seminar

May 9 -13, 2022
Hybrid at the Physikzentrum Bad Honnef/Germany

WILHELM UND ELSE HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the 766. WE-Heraeus-Seminar:

The search for New Physics beyond the Standard Model of particles and interactions is one of main challenges of modern science. Beside the ultrarelativistic collision experiments at large-scale facilities, such as Large Hadron Collider in CERN, the signals of New Physics might be detected in low-energy measurements of atomic and molecular systems. These measurements are complementary to the "LHC-like" physics and greatly benefit from their very high accuracy. Indeed, recent advances of laser cooling and trapping techniques, frequency and time metrology, as well as quantum control and measurement methods open up routes for unprecedentedly high-accuracy studies in atomic, molecular and optical (AMO) physics. These studies will be in the focus of the Heraeus seminar "High-precision measurements and searches for New Physics". The goal of the seminar is to provide the *widest possible* overview of AMO and related activities aiming at discovery of new particles and associated fields beyond those known in the Standard Model. The world-recognized experts, young researchers and students will come together to discuss both the ongoing and future high-precision AMO experiments and technical breakthroughs behind them. Special attention will be paid to the spectroscopic measurements in atomic traps and (low-energy) ion storage rings, searches for light Dark Matter and for violations of fundamental symmetries of Nature, studies with exotic and antimatter atomic systems, as well as to applications of atomic clocks and quantum sensor networks for the detection of exotic fields. The detailed discussion of experimental results and advances, will be naturally complemented by the presentations of world-recognized theoreticians who will put the high-precision AMO measurements in the general framework of testing of fundamental physics.

Scientific Organizers:

Prof. Dr. Klaus Blaum	Max-Planck-Institut für Kernphysik, Heidelberg E-mail: klaus.blaum@mpi-hd.mpg.de
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Introduction

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Registration:

Martina Albert (WE Heraeus Foundation)
at the Physikzentrum, reception office
Sunday (17:00 h – 21:00 h) and Monday
morning

Program

Program

Sunday, May 8, 2022

17:00 – 21:00	Registration	
from 18:30	*BUFFET SUPPER / Informal get together*	
20:00 – 21:00	**Welcome lecture** Dmitry Budker	**Hunting elephants in a room: new ways to search for dark matter and other adventures**

Monday, May 9, 2022

07:30	*BREAKFAST*	
08:45 – 09:00	Scientific organizers	**Opening and welcome**
09:00 – 09:45	Marianna Safronova	**Searches for new physics with quantum sensors in the laboratory and in space**
09:45 – 10:30	Jun Ye	**Quantum system engineering and sensing for fundamental physics**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Jörg Jaeckel	**News on Sub-eV Feebly Interacting Particles**
11:45 – 12:30	Dionysios Antypas	**Precision experiments in search for new physics**
12:30	**Conference Photo** (in the foyer of the lecture hall)	
12:40	*LUNCH*	

Program

Monday, May 9, 2022

14:00 – 14:45	Tanya Zelevinsky	**Lattice clock based on molecular vibrations**
14:45 – 15:30	Robert Berger	**Probing violations of fundamental symmetries with polyatomic molecules**
15:30 – 16:00	*COFFEE BREAK*	
16:00 – 16:45	Mikhail G. Kozlov (online)	**Antisymmetric J-Coupling Experiment in a TlF Molecular Beam**
16:45 – 17:30	Zheng-Tian Lu (online)	**Measurement of the Electric Dipole Moment of of ^{171}Yb Atoms in an Optical Dipole Trap**
17:30 – 19:00	**Poster session 1**	
19:00	*DINNER*	

Program

Tuesday, May 10, 2022

08:00	*BREAKFAST*	
09:00 – 09:45	Piet O. Schmidt	**Highly Charged Ion Optical Clocks to Test Fundamental Physics**
09:45 – 10:30	José Crespo López-Urrutia	**Extreme-ultraviolet frequency combs and highly charged ions**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Sergey Eliseev	**Ultra-precise mass-ratio spectrometry with PENTATRAP for various aspects of fundamental physics**
11:45 – 12:30	Randalf Pohl	**Charge radii of the lightest nuclei**
12:30	*LUNCH*	
14:00 – 14:45	Elina Fuchs	**Searching for light Dark Sectors with isotope shifts**
14:45 – 15:30	Deniz Aybas	**Searches for the ultralight bosonic dark matter**
15:30 – 16:15	Roee Ozeri (online)	**Quantum Information Techniques in searches of physics beyond the standard model and the detection of ultra-cold collisions**

Program

Tuesday, May 10, 2022

16:15 – 16:50	*COFFEE BREAK*	
	Progress reports	
16:50 – 17:10	Abhishek Banerjee	**Complementarity between equivalence principle tests and precision tests**
17:10 – 17:30	Melina Filzinger	**New prospects for tests of local Lorentz invariance via microwave spectroscopy of the $^{171}Yb^{+}$ F-state**
17:30 – 17:50	Madeline Bernstein	**Precision measurement of the fine-structure constant**
17:50 – 18:10	Annabelle Kaiser	**High-precision g-factor measurements of $^{3}He^{+}$ and $^{3}He^{2+}$**
18:10 – 18:30	Anna Viatkina	**Nuclear polarization effects in atoms and ions**
18:30 – 18:50	Stergiani Marina Vogiatzi	**Muonic atom spectroscopy with radioactive targets**
18:50 – 19:10	Felix Kröger (online)	**High-Resolution Microcalorimeter Measurement of X-Ray Transitions in He-like Uranium at CRYRING@ESR**
19:20	*DINNER*	

Program

Wednesday, May 11, 2022

08:00	*BREAKFAST*	
09:00 – 09:45	Eberhard Widmann	**In-beam hyperfine spectroscopy of (anti-)hydrogen**
09:45 – 10:30	Masaki Hori	**Laser spectroscopy of antiprotonic helium and pionic helium atoms**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Eve V. Stenson	**Matter-antimatter pair plasmas: a new frontier in plasma physics**
11:45 – 12:30	Ariel Zhitnitsky	**Axion Quark Nuggets and Matter-Antimatter asymmetry as two sides of the same coin: theory, observations and future experimental searches**
12:30	*LUNCH*	
14:00 – 17:30	**Excursion** (leisurely hike in the vicinity)	
17:30 – 19:00	**Poster session 2**	
19:00	*DINNER*	
20:00 – 21:00	**Evening lecture** Fabiola Gianotti	**Physics beyond the Standard Model at highest energies**

Program

Thursday, May 12, 2022

08:00	*BREAKFAST*	
09:00 – 09:45	Hans Stroeher	**Storage Rings: From Hadron Physics to Precision Measurements**
09:45 – 10:30	Yuri Litvinov	**Precision Experiments at the Intersection of Atomic, Nuclear and Astro-Physics**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Yannis Semertzidis	**The hybrid-symmetric storage ring lattice for a high sensitivity proton EDM experiment**
11:45 – 12:30	Magdalena Kowalska (online)	**Precision studies with polarised unstable nuclei**
12:30	*LUNCH*	
14:00 – 16:00	**Helmholtz Prize Ceremony**	
	Joachim Ullrich	**High-Precision Measurements and Searches for New Physics**
16:00	**RECEPTION**	
17:45	Start to the shipping pier (about 20 minutes walk)	
19:00	JOINT DINNER on board cruising by the boat “MS Moby Dick” on the river Rhine	

Program

Friday, May 13, 2022

08:00	*BREAKFAST*	
09:00 – 09:45	Anna Soter (online)	**Low energy particle physics experiments at PSI in the lepton sector**
09:45 – 10:30	Ferdinand Schmidt-Kaler	**Seaching for new physics with cold trapped ions**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Andrew Geraci (online)	**Searching for fifth forces, non-Newtonian gravity, and dark matter with AMO-based sensors**
11:45 – 12:30	Joel Bergé (online)	**MICROSCOPE and the search for a fifth force**
12:30 – 12:45	Scientific organizers	**Poster awards, summary and closing remarks**
12:45	*LUNCH*	

End of the seminar *and FAREWELL COFFEE* **/ Departure**

Please note that there will be ***no*** *dinner at the Physikzentrum on Friday evening for participants leaving the next morning.*

Posters

Posters 1

1	Khwaish Anjum	**Laser-Microwave Double-Resonance Spectroscopy to Perform g-factor Measurements of Heavy, Highly Charged Ions at ARTEMIS in HITRAP**
2	Thomas Battard	**Electron EDM measurement with cesium in argon matrix**
3	Hendrik Bekker	**Probing the axion gradient-coupling with nuclear magnetic resonance spectroscopy**
4	Olesia Bezrodnova	**LIONTRAP: Towards High-Precision Mass Measurements Of The Helium-3 And Tritium Nuclei**
5	Matthew Bohman	**Precision Measurements with Trapped Ion Atomic Clocks at the Lifetime and Systematic Limit**
6	Florin Lucian Constantin	**Precision measurements with cold trapped HD+ ions for THz electric field characterization**
7	Skyler Degenkolb	**New tools for preparing, preserving, and detecting polarized spins**
8	Sophia Florence Dellmann	**Proton capture on stored radioactive ions**
9	Elwin Dijck	**Dynamics of mixed species Coulomb crystals with highly charged ions in a superconducting Paul trap**
10	Eugen Dizer	**Hadronic Vacuum Polarization Corrections in Highly Charged Ions**
11	Menno Door	**High-precision mass-ratio measurements of ytterbium isotopes and absolute mass measurement of 20Ne with the Penning-trap mass spectrometer Pentatrap**

Posters 1

12	Yurii Dumin (online)	**New Physics from the Low-Multipole Part of the CMB Spectrum**
13	Pavel Fadeev	**Shifting lines: nuclear & atomic transitions in search for new bosons and variations in fundamental constants**
14	Konstantin Gaul	**Selecting atoms and molecules tailored for robust bounds on fundamental sources of P,T-violation in a global analysis**
15	Peter Granum	**A Gravity Measurement of Antihydrogen**
16	Mehedi Hasan	**Observation of Anisotropic Zitterbewegung in Non-Abelian Gauge Field**
17	Tobias Heldt	**Towards intra-cavity nonlinear laser excitation of the thorium-229 isomeric state**
18	Feodor Karpeshin	**Physics of laser-assisted nuclear processes as the base for creation of the nuclear clock**
19	Carina Killian	**Towards the first demonstration of gravitational quantum states of atoms with a cryogenic hydrogen beam**
20	Charlotte König	**Hyperfine Spectroscopy of Single Molecular Hydrogen Ions in a Penning Trap at Alphatrap**
21	Kathrin Kromer	**Direct high precision measurement of the Q-value of the electron capture in 163Ho and metastable states in highly charged ions**

Posters 2

22	Sebastian Lahs	**First results towards a measurement of the electron EDM in a cryogenic matrix**
23	Ali Lezeik	**Measuring Gravity with VLBAI**
24	Lothar Maisenbacher	**Precision spectroscopy of the 2S-6P transition in atomic hydrogen**
25	Andres Martinez de Velasco	**Towards Ramsey-Comb Spectroscopy of Hydrogen-like Helium**
26	Victor Jose Martinez Lahuerta	**Ab initio quantum theory of mass defect and time dilation in trapped-ion optical clocks**
27	Jonathan Morgner	**Stringent Tests of QED by Measuring Bound-Electron g Factors in Highly Charged Tin**
28	Jan-Hendrik Oelmann	**An XUV frequency comb for precision spectroscopy of highly charged ions**
29	Natalia Oreshkina	**New-physics contributions and "photon-bridge" effects to the energy levels in simple ions**
30	Philip Pfäfflein	**High-Resolution Measurement of X-Ray Transitions in He-like Uranium at CRYRING@ESR**
31	Till Rehmert	**Towards Quantum Logic Spectroscopy of Single Molecular Ions**
32	Jan Richter	**Parity-Violation Studies with Partially Stripped Ions**
33	Mikio Sakurai	**muEDM: Search for the muon EDM using the frozen-spin technique at PSI**

Posters 2

34	Sangeetha Sasidharan	**High-precision determination of the atomic mass of Helium-4**
35	Bastian Sikora	**Two-loop self-energy correction to the bound-electron g-factor: update M-term**
36	Romain Soguel	**Gauge invariant subsets in two-photon-exchange diagrams resulting from a redefined vacuum approach**
37	Jonas Sommerfeldt	**Coulomb Corrections to Delbrück Scattering**
38	Martin Steinel	**A dual-species optical clock to investigate variations of the fine-structure constant and test local position invariance**
39	Csilla Szabo-Foster (online)	**Traceability of x-ray energy scales**
40	Sebastian Ulbricht	**Relativistic effects of gravity in Earth-based optical cavities**
41	Christian Warnecke	**A superconducting radio-frequency quadrupole resonator for metrology experiments with highly charged ions**
42	Christian Will	**Sympathetic cooling of separately trapped ions coupled via image currents**
43	Vitaly Wirthl	**Precision spectroscopy of the 2S-6P transition in atomic deuterium**
44	Binghui Zhu	**X-ray Emission Study Performed for Hydrogen-like Lead Ions at the Electron Cooler of CRYRING@ESR**

Abstracts of Lectures

(in alphabetical order)

Precision experiments in search for new physics

<u>D. Antypas</u>[1]

[1]*Johannes Gutenberg-Universität Mainz, Helmholtz-Institut Mainz, Mainz 55128, Germany*

Spectroscopy of atomic or molecular probes in tabletop apparatus can provide a range of tests of fundamental physics. The high measurement precision attainable in such experiments can be employed to investigate physics beyond the standard model of particle physics. I will discuss two discrete avenues within this so-called precision frontier. In one of them, we employ precision isotope shift spectroscopy in an optical transition in ytterbium (Yb) to check a hint for new physics that resulted from related work in ionic Yb, and help identify the origin of the possible new physics signal. In another experimental program, we carry out searches for fundamental constant oscillations which are expected within ultralight dark matter scenarios. With a bundle of spectroscopy-based experiments employing atomic or molecular samples, we look for minute oscillations in the fine structure constant, the electron and nuclear mass, and sensitively constrain the respective dark matter couplings to matter within a broad range in the oscillation frequency spanning six or more orders of magnitude.

Searches for the ultralight bosonic dark matter

D. Aybas[1,2]

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[2]Boston University, USA

Axions (or axionlike particles in general) are prominent candidates to be the dark matter. There are many experimental approaches to search for axions at different masses, and we are searching for ultralight axions with a number of table-top experiments. Cosmic Axion Spin Precession Experiments (CASPEr) are based on the nuclear magnetic resonance (NMR) measurement of ensemble of spins [1]. The CASPEr-electric setup in Boston uses a polarized ferroelectric crystal that is sensitive to axion-gluon coupling that induces an oscillating nuclear electric dipole moment (EDM) due to the effective electric field across the sample [2]. The CASPEr-gradient setup in Mainz uses hyperpolarized xenon and precision magnetometry with superconducting quantum interference devices (SQUIDs) to search for the axion-nucleon coupling [3]. In addition, the CASPEr-ZULF sideband setup in Mainz uses zero-to-ultralow field NMR measurements to search for sidebands due to axion gradient effect [4] and the CASPEr-ZULF comagnetometer searches for sidebands in NMR spectra of nuclear spins due to the axion-nucleon coupling [5]. The SHAFT (Search for Halo Axions with Ferromagnetic Toroids) experiment in Boston uses SQUIDs to search for an oscillating magnetic field induced by background axions in the presence of a static magnetic field, which is enhanced by a ferromagnetic core [6]. What these searches have in common is their high sensitivity to magnetic fields, the sensitivity calibrations with known measurements, and the data analysis methods that are used to distinguish any axion candidate signals from noise that require the knowledge of the expected signal lineshapes due to different axion couplings for optimal filtering [7].

References

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2. D. Aybas, et al., PRL **126**, 141802 (2021)
3. A. Garcon, et al., Quantum Sci. Technol. **3**, 014008 (2018)
4. A. Garcon, et al., Science Advances **5**, (2019)
5. T. Wu, et al., PRL **122**, 191302 (2019)
6. A. V. Gramolin, et al., Nature Physics **17**, 79-84 (2021)
7. A. V. Gramolin, et al., PRD **105**, 035029 (2022)

COMPLEMENTARITY BETWEEN EQUIVALENCE PRINCIPLE TESTS AND PRECISION TESTS

Abhishek Banerjee

Weizmann Institute of Science, Rehovot, Israel

A possible implication of an ultralight dark matter field interacting with the Standard Model (SM) degrees of freedom is oscillations of fundamental constants. I will explain how to establish the direct experimental bounds on the coupling of an oscillating UDM to various fundamental constants of nature using precision measurements. Furthermore, I will discuss how the Equivalence Principle (EP) tests can constraint the existence of a light scalar. Lastly, I will explain (phenomenologically) the complementarity between the EP tests and Precision tests and also provide a theoretical insight.

References

[1] Tretiak et. al. arXiv: 2201.02042 (submitted to Physical Review Letters)
[2] Oswald et. al. arXiv: 2111.06883 (submitted to Physical Review Letters)

MICROSCOPE and the search for a fifth force

Joel Bergé
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The MICROSCOPE mission allowed for an unprecedented precision on the test of the Weak Equivalence Principle (WEP). It relied on comparing the free fall of two test masses of different compositions as they orbited the Earth. Beside testing General Relativity's foundation, it allowed us to shed light on modified gravity models involving the existence of a putative fifth force. For instance, the test of the equivalence principle in the Earth orbit sets constraints on long-range (of order a thousand kilometres and more) fifth forces, while the interaction of MICROSCOPE's test masses with each other provides clues on a shorter (of order 0.1 m) fifth force.
In this talk, I will first present MICROSCOPE's measurement concept, with an emphasis on the test of the WEP. In particular, I will discuss systematic effects and potential routes for improvements. I will then show that technical data allowed us to look for short-range forces through the interaction between test masses. Finally, I will discuss how MICROSCOPE could set new constraints on models such as a Yukawa deviation from Newtonian gravity, a light dilaton and a chameleon field.

Probing violations of fundamental symmetries with polyatomic molecules

R. Berger[1]

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In this presentation, I will discuss opportunities that polyatomic molecules provide in the search for violations of fundamental symmetries: **I**) Chiral molecules feature, due to nearly vanishing tunneling splittings [1-3], close-lying levels of opposite parity (P), which can lead to a huge enhancement of electroweak and cosmic P-odd, but time-reversal even (T-even) effects [3-5]. The most intriguing of these is a P-odd energy difference between enantiomers [3], which has also been discussed, among other effects [6], as a source for biomolecular homochirality (see [3] and references therein). I intend to outline a recent experimental scheme to address fundamental properties of chiral molecules by matterwave interference [2] and highlight possibilities to cool chiral molecules with lasers [7]. **II**) Achiral laser-cooled molecules, like alkaline earth hydroxides [7,8], can serve as sensitive probes for P,T-odd fundamental interactions and nuclear moments, the molecular enhancement factors of which can be estimated efficiently [9]. Additionally, we have identified molecular highly charged ions (HCIs) as a promising system class [10], which combines favourable features of polar molecules with advantages of atomic HCIs. These molecular HCIs allow to search e.g. for Schiff moments of deformed nuclei [10] or for variations of fundamental constants. Further progress in laser-cooling of molecules might also allow to explore such variations via intermolecular correlation effects [11].

References

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[2] B. A. Stickler, M. Diekmann, R. Berger, D. Wang, Phys. Rev. X **11**, 031056 (2021)
[3] R. Berger, J. Stohner, WIREs Comput. Mol. Sci. **9**, e1396 (2019)
[4] S. A. Brück, N. Sahu, K. Gaul, R. Berger, arXiv:2102.09897
[5] K. Gaul, M. G. Kozlov, T. A. Isaev, R. Berger, Phys. Rev. Lett. **125**, 123004 (2020); Phys. Rev. A **102**, 032816 (2020)
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Precision measurement of the fine-structure constant

M. Bernstein,[1] Z. Pagel,[1] J. Roth,[1] Y. Segev,[1] A. Neely,[1] S. Bie,[1] O. Zhou,[1] H. Müller[1 2]

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Precision measurements of the fine structure constant α provide a powerful opportunity to test the Standard Model of particle physics. We can directly measure α via the atomic recoil, or α can be determined from measurement of the electron g-2 anomaly combined with Standard Model theory [1]. Comparing the results of these different measurement techniques constitutes a sensitive test of the Standard Model. We are conducting a precision measurement of α via the recoil frequency of cesium atoms in an atomic fountain. Previous recoil-based measurements of α have reached accuracies of 200 parts per trillion (ppt) at Berkeley [2] and 81 ppt at LKB [3], while the electron g-2 measurement has reached 240 ppt uncertainty [1]. The two most recent recoil-based measurements have slight tensions with the electron g-2 measurement, and additionally a strong tension between themselves, deviating from g-2 in opposite directions. Our next measurement at Berkeley seeks a sensitivity of 20 ppt. We have constructed a 5-m tall atomic fountain, which will use Bragg diffraction and Bloch oscillations to impart a large momentum splitting in the atomic wavefunction. The interferometer laser beam will be large and homogenous, reducing systematic effects and loss of contrast caused by wavefront curvature and speckle. To that effect, our vacuum chamber is 50 cm wide and can accommodate beam waists of up to 5 cm, ten times the beam waist used in our group's previous measurement [2].

References

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[3] Morel et al, Nature **588,** 61-65 (2020)

Extreme-ultraviolet frequency combs and highly charged ions.

José R. Crespo López-Urrutia

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Relativistic, quantum electrodynamic, and nuclear size effects affecting the outer electron become very large in highly charged ions (HCI). With less bound electrons, the electronic structure of many isoelectronic sequences of HCI becomes easier to calculate. In addition, their great variety makes systematic investigation of fundamental effects as a function of the nuclear charge possible. HCI are excellent references for optical frequency metrology [1] and investigation of the time variation of fundamental constants [2], and recent experiments of the PTB-MPIK collaboration have shown their potential [3,4,5], also in the context of King-plot analyses [5]. HCI possess many extremely forbidden photon transitions of high multipolarity (as e. g. experimentally found in Ref. [6]) up to the x-ray region, while being protected from photoionization by their high binding energies. Thus, they can also serve for stabilizing extreme ultraviolet frequency (XUV) combs, and enable frequency metrology beyond the optical. We are preparing in collaboration with PTB an experiment including a superconducting RF trap [7] and an XUV frequency comb [8] to explore this region with HCI. At higher photon energies, the searches for new physics should become very sensitive, since more deeply bound electrons can be accessed than in the optical range.

References

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Ultra-precise mass-ratio spectrometry with PENTATRAP for various aspects of fundamental physics

M. Door[1], S. Eliseev[1], P. Filianin[1], J. Herkenhoff[1], K. Kromer[1], D. Lange[1], Yu. Novikov[2], Ch. Schweiger[1] and K. Blaum[1]

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[2] PNPI, St. Petersburg, Russia

High-precision Penning trap mass spectrometry is the most precise technique employed to measure masses of nuclides with half-lives as short as a few ten ms. Currently, there are about a dozen high-precision Penning-trap mass spectrometers located in North America and Europe. The majority of them are part of various Rare Ion Beam (RIB) facilities and aim at measurements of masses of short-lived nuclides with fractional uncertainties down to 10^{-9}. The other group encompasses four ultra-precise Penning trap mass spectrometers. Their major goal are mass-ratio measurements on long-lived and stable nuclides with fractional uncertainties of as small as a few ppt.

In this second group the PENTATRAP experiment is probably the most advanced. It is located at the Max-Planck Institute for nuclear physics and aims to perform mass-ratio measurements on a very broad range of long-lived nuclides to assist, e.g., experiments on the determination of the neutrino mass, on the search for the fifth force, on the investigation of atomic metastable states that can be suitable ion clock transitions and so on. In this talk I will (after a quite detailed introduction of Penning-trap mass spectrometry) present latest achievements and future plans with PENTATRAP.

New prospects for tests of local Lorentz invariance via microwave spectroscopy of the $^{171}Yb^{+}$ F-state

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The Yb^{+} electronic F-state is well suited for tests of local Lorentz invariance (LLI) in the electron-photon sector. It features an enhanced sensitivity to possible LLI-violating effects due to the orbital's large kinetic energy and anisotropic momentum distribution, as well as a yearslong lifetime which enables long interrogation times [1]. Tight constraints on Lorentz symmetry violation parameters for electrons have been obtained by comparison of two single-ion $^{171}Yb^{+}$ optical clocks [2]. However, the coherent interrogation time in optical frequency comparisons is limited by ion heating and finite laser coherence, in this case to less than a second. Consequently, averaging of about 45 days of measurement data was needed to reach a statistical uncertainty below 2 mHz. In contrast, microwave radiation generally features longer coherence times than lasers, and its wavelength in the cm-range renders ion heating inconsequential. We achieve seconds-long coherent interrogation of the $^{171}Yb^{+}$ $^{2}F_{7/2}$ F=3 → F=4 hyperfine transition at 3.6 GHz on a single trapped ion, limited only by background magnetic field noise. This enables us to resolve mHz shifts within hours of averaging. Lorentz symmetry testing can be performed by comparing the resonant microwave frequencies of transitions that involve different $|m_F|$ sublevels of the hyperfine states, and thus feature varying sensitivities to LLI violations. To suppress the linear Zeeman shift and associated energy fluctuations, we use dynamical decoupling pulse sequences to coherently average the energy of $\pm m_F$ Zeeman pairs in a static magnetic field.

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Searching for light Dark Sectors with isotope shifts

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Abstract

New light bosons beyond the Standard Model may play a role as Dark Matter or a mediator to a Dark Sector. I will present how such particles that couple to neutrons and electrons can be probed by precision isotope shift spectroscopy.

In addition to current and expected bounds on new light bosons from the linearity of several isotope shifts in a so-called King plot, I will highlight new avenues with Rydberg states, allowing for the use of less isotopes. Beyond the scenario of a generic long-range interaction, I will also show the application to different well-motivated particle physics models that contain a light new boson.

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Searching for fifth forces, non-Newtonian gravity, and dark matter with AMO-based sensors

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The QCD axion is a particle postulated to exist to solve the Strong CP problem. The axion could also constitute the Dark matter in the universe, thus making it an "economical" solution to two of the greatest puzzles in cosmology and high-energy physics. Axions can generate novel spin-dependent short-range "fifth-forces" between nuclei. The Axion Resonant InterAction Detection Experiment (ARIADNE) is a collaborative effort to search for the QCD axion, using a technique based on nuclear magnetic resonance. The aim is to detect an axion-mediated short-range interaction between laser-polarized 3He nuclei and an unpolarized tungsten source mass. The experiment has the potential to probe deep within the theoretically interesting regime for the QCD axion in the mass range of 0.01-10 meV. In this talk I will discuss the basic principle of the experiment and the current experimental status. As another method to search for the QCD axion, I will describe work towards the realization of a tabletop high-frequency gravitational wave detector based on optically levitated dielectric objects. The Levitated Sensor Detector (LSD) will be highly sensitive in the frequency band around 100 kHz, promising for detection of gravitational waves resulting from the annihilations of Grand-Unified Theory-scale QCD axions which can form in clouds around Black Holes in our galaxy via the Superradiance process. Finally, I will describe how similar techniques with optically levitated dielectric objects can be used to search for other physics beyond the standard model, including corrections to Newtonian gravity at short range.

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Laser spectroscopy of antiprotonic helium and pionic helium atoms

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Metastable antiprotonic helium ($\bar{p}He^+$) is an exotic atom composed of a helium nucleus, electron, and an antiproton occupying a Rydberg state with principal and orbital angular momentum quantum numbers of $n \approx l-1 \approx 38$. It is among the hadron-antihadron bound systems with the longest known lifetimes. By utilizing sub-Doppler two-photon laser spectroscopy [1] or buffer gas cooling [2], its atomic transition frequencies were measured to ppb-scale precision. Comparisons with the results of QED calculations allowed the antiproton-to-electron mass ratio to be determined as 1836.1526734(15). The results were used to set upper limits on fifth forces between antiprotons and nucleons at atomic length scales, and on forces that may arise between an electron and antiproton mediated by hypothetical bosons. Efforts are currently underway to improve the experimental precision using CERN's ELENA facility.

We observed [3] narrow spectral lines of $\bar{p}He^+$ formed in superfluid helium with a surprisingly high spectral resolution of 2 parts per million. This revealed the hyperfine structure arising from the spin-spin interaction between the antiproton and electron, despite the fact that the atom was surrounded by a dense matrix of normal atoms. This phenomenon may imply future possibilities in condensed matter or astrophysical fields.

Metastable pionic helium (πHe^+) contains a negative pion occupying a state of $n \approx l-1 \approx 17$ [4], and retains a 7 ns average lifetime. We recently used the 590 MeV ring cyclotron facility of PSI to synthesize the atoms, and irradiated them with resonant infrared laser pulses. This induced a pionic transition $(n,l)=(17,16)\rightarrow(17,15)$ and triggered an electromagnetic cascade that resulted in the π^- being absorbed into the helium nucleus. This constitutes the first laser excitation and spectroscopy of an atom containing a meson. By improving the experimental precision, the pion mass may be determined to a high precision as in the antiproton case.

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News on Sub-eV Feebly Interacting Particles

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This talk will discuss some recent developments in the search for axions and axionlike particles. We will have a look both from the model-building side but also highlight a few experimental and observational aspects.

High-precision g-factor measurements of $^{3}He^{2+}$

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The Heidelberg 3He-experiment is aiming at the first direct high-precision measurement of the nuclear magnetic moment of $^{3}He^{2+}$, with a relative uncertainty on the 10^{-9} level. The helion nuclear magnetic moment is an important parameter for the development of hyperpolarized 3He-NMR-probes for absolute magnetometry.

The measurement is performed using a cryogenic four Penning-trap setup, with techniques presented in [1]. To achieve the mandatory frequency stability for spin-state detection, a single $^{3}He^{2+}$ ion will be prepared at temperatures of a few mK via sympathetic laser cooling with $^{9}Be^{+}$. To further improve the stability, the noise generated by the voltage sources applied to the trap electrodes can be reduced by implementing Josephson junctions as a voltage source. The tuning will be achieved by switching a low-noise DAC in series to the Josephson junctions, aiming at an absolute voltage stability better than 70nV over two minutes. The setup and status of the project will be presented.

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High-Resolution Microcalorimeter Measurement of X-Ray Transitions in He-like Uranium at CRYRING@ESR

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Helium-like ions are the simplest atomic multibody systems and their study along the isoelectronic sequence provides a unique testing ground for the interplay of the effects of correlation, relativity and quantum electrodynamics [1,2]. However, for high-Z ions with nuclear charge Z larger 54, where inner-shell transition energies reach up to 100 keV, there are currently no data available to challenge state-of-the-art theory. In this context the recent development of metallic magnetic calorimeter (MMC) detectors is of particular importance [3]. Their high spectral resolution below 100 eV FWHM at 100 keV incident photon energy in combination with a broad spectral acceptance down to a few keV will enable new types of precision x-ray studies.

I will report on the application of MMC detectors for high resolution x-ray spectroscopy at the electron cooler of the low energy storage ring CRYRING@ESR at GSI, Darmstadt. Within this experiment, the x-ray emission associated with radiative recombination of cooler electrons and stored hydrogen-like uranium ions was studied. For this purpose, two MMC detectors developed within the SPARC collaboration were placed under 0° and 180° with respect to the ion beam axis. Special emphasis will be given to the achieved energy resolution of better than 90 eV at x-ray energies close to 100 keV which enables for the very first time to resolve the substructure of the $K\alpha_1$ and $K\alpha_2$ lines as well as to the various aspects resulting from the selected detection geometry in combination with the broad spectral acceptance.

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Precision Experiments at the Intersection of Atomic, Nuclear and Astro-Physics

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The storage of freshly produced radioactive particles in a storage ring is a straightforward way to achieve the most efficient use of the rare. Employing storage rings for precision physics experiments with highly-charged ions (HCI) at the intersection of atomic, nuclear, plasma and astrophysics is a rapidly developing field of research. Until very recently, there were only two accelerator laboratories, GSI Helmholtz Center in Darmstadt, Germany (GSI) and Institute of Modern Physics in Lanzhou, China (IMP), operating heavy-ion storage rings coupled to radioactive-ion production facilities. The experimental storage ring ESR at GSI and the experimental cooler-storage ring CSRe at IMP offer beams at energies of several hundred A MeV. The ESR is capable to slow down ion beams to as low as 4 A MeV (β=0.1). Beam manipulations like deceleration, bunching, accumulation, and especially the efficient beam cooling as well as the sophisticated experimental equipment make rings versatile instruments. The number of physics cases is enormous. The focus here will be on the most recent highlight results achieved within FAIR-Phase 0 research program at the ESR.

The performed experiments will be put in the context of the present research programs at GSI/FAIR and in a broader, worldwide context, where, thanks to fascinating results obtained at the presently operating storage rings, a number of new exciting projects is planned. Experimental opportunities are being now dramatically enhanced through construction of dedicated low-energy storage rings, which enable stored and cooled secondary HCIs in previously inaccessible low-energy range. Thanks to the fascinating results obtained at the ESR and the CSRe as well as to versatile experimental opportunities, there is now an increased attention to the research with ion-storage rings worldwide.

Measurement of the Electric Dipole Moment of ^{171}Yb Atoms in an Optical Dipole Trap

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The permanent electric dipole moment (EDM) of the ^{171}Yb (I = 1/2) atom is measured with atoms held in an optical dipole trap (ODT). By enabling a cycling transition that is simultaneously spin-selective and spin-preserving, a quantum non-demolition measurement with a spin-detection efficiency of 50% is realized. A systematic effect due to parity mixing induced by a static E field is observed, and is suppressed by averaging between measurements with ODTs in opposite directions. The coherent spin precession time is found to be much longer than 300 s. The EDM is determined to be d(^{171}Yb) = (- 4.7 ± 5.7_{stat} ± 1.2_{syst})E-27 e cm, leading to an upper limit of |d(^{171}Yb)| < 1.4E−26 e cm (95% C.L.). These measurement techniques can be adapted to search for the EDM of ^{225}Ra.

Quantum Information Techniques in searches of physics beyond the standard model and the detection of ultra-cold collisions

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In this talk I will review two trapped-ion experiments in which we used techniques the were developed in quantum information science for new physics searches as well as the measurement of collision cross-sections between trapped-ions and ultra-cold atoms.

In the first experiment [1], we measured the isotope shift of a narrow optical-clock transition between two isotopes of Sr^+ with a relative uncertainty of 1.6×10^{-11} using a two-isotope entangled state. This measurement also revealed a relative difference of $3.46(23)\times10^{-8}$ in the orbital magnetic susceptibility of the electrons in the excited electronic state of the clock transition. The precise measurement of atomic isotope shifts is important in order to improve on the bounds the existence of new scalar forces.

In a second experiment, we used the technique of quantum-logic in order to measure the cross-section of different collisions between a trapped-ion and ultra-cold atoms [2]. Similarly to quantum-logic spectroscopy, in which a logic-ion is used to readout the interaction of a spectroscopy-ion with light, we use a logic-ion in order to detect the energy and momentum imparted to a chemistry-ion in an inelastic or a reactive collision. We study this way the dynamics of spin exchange in collisions between all stable isotopes of Sr^+ with ultracold Rb, as well as charge exchange between Rb^+ and Rb.

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Charge radii of the lightest nuclei

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Laser spectroscopy of simple atoms is sensitive to properties of the atomic nucleus, such as its charge and magnetization distribution, or its polarizability. This allows determining the nuclear parameters from atomic spectroscopy, but also limits the attainable precision for the determination of fundamental constants or the test of QED and the Standard Model.

In light muonic atoms and ions, one negative muon replaces all atomic electrons, resulting in a calculable hydrogen-like system. Due to the muon's large mass (200 times the electron mass), the muon or bits the nucleus on a 200 times smaller Bohr radius, increasing the sensitivity of muonic atoms to nuclear properties by 200^3 = 10 million.

Our laser spectroscopy of muonic hydrogen through helium has resulted in a 10fold increase in the precision of the charge radius of the proton [1], deuteron [2], and helium-4 [3]. Next we're measuring the hyperfine splitting in muonic hydrogen to obtain information about the magnetization of the proton [4]. In Mainz, we're setting up an experiment to determine the triton charge radius by laser spectroscopy of atomic tritium [4].

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Searches for new physics with quantum sensors in the laboratory and in space

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The last decade has seen unprecedented effort in dark matter model building at all mass scales coupled with the design of numerous new detection strategies. Transformative advances in quantum technologies have led to a plethora of new high-precision quantum sensors and dark matter detection strategies for ultralight bosonic dark matter [1]. I will give an overview of ultralight scalar dark matter (UDM) searches and focus on UDM searches with atomic and nuclear clocks. I will discuss recent advances in theory of novel clocks based on highly-charged ions and efforts to develop a nuclear clock. Recent ideas on dark matter searches and test of general relativity with clocks in space [2, 3] will be discussed. I will also report a release of the new version of an online portal for high-precision atomic data and computation [4]. Future plans to add data for more systems as well as to release computer codes are discussed.

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Highly Charged Ion Optical Clocks to Test Fundamental Physics

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Highly charged ions (HCI) have many favorable properties for tests of fundamental physics and as potential next-generation optical atomic frequency standards [1]. For example, narrow optical fine-structure transitions have smaller polarizabilities and electric quadrupole moments, but much stronger relativistic, QED and nuclear size contributions to their binding energy compared to their (near) neutral counterparts. Therefore, HCI have been found to be among the most sensitive atomic species to probe for a possible variation of the fine-structure constant or dark matter coupling.
HCI can readily be produced and stored in an electron beam ion trap (EBIT). There, the most accurate laser spectroscopy on any HCI was performed on the 17 Hz wide fine-structure transition in Ar^{13+} with 400 MHz resolution, lagging almost twelve orders of magnitude behind state-of-the-art optical clocks. This was primarily limited by Doppler broadening of the megakelvin hot ion plasma in the EBIT [2]. The lack of a suitable optical transition for laser cooling and detection can be overcome through sympathetic cooling with a co-trapped Be^+ ion [3]. Techniques developed for quantum information processing with trapped ions can be used to perform quantum logic spectroscopy [4]: A series of laser pulses transfers the internal state information of the Ar^{13+} ion after spectroscopy onto the Be^+ ion for efficient readout.
We present the first coherent laser spectroscopy and optical clock operation of a HCI. Ar^{13+} are extracted from a compact EBIT [5], charge-to-mass selected and injected into a cryogenic Paul trap containing a crystal of laser-cooled Be^+ ions [6]. By removing excess Be^+ ions, a crystal composed of a Be^+/Ar^{13+} ion pair is obtained. Results on sympathetic ground state cooling and quantum logic spectroscopy of the Ar^{13+} $P_{1/2}$-$P_{3/2}$ fine-structure transition at 441 nm will be presented, improving the precision of the observed line center by more than eight orders of magnitude [7]. A full error budget for the Ar^{13+} HCI clock and absolute frequency as well as isotope shift measurements between $^{36,40}Ar^{13+}$ will be presented [8]. Finally, prospects for 5th force tests based on isotope shift spectroscopy of Ca^+/Ca^{14+} isotopes [9] and the high-sensitivity search for a variation of the fine-structure constant using HCI will be presented [1].

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Seaching for new physics with cold trapped ions

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Quantum technologies allow for fully novel schemes of computing, simulation and sensing. We employ trapped ions in modern segmented ion traps as scalable and freely reconfigurable qubit register [1]. This technologies of trapping, (sympathetic) cooling and spectroscopy are avalable for searching for new physics [2]. I discuss the aims and the progress of the TACTICA experiment, where Ca+ ions are employed to serve for tagging [3] the arrival of Th intruder ions, that are injected from an external source. Also, Ca+ is used for sympathetic cooling [4].
We plan for reading out the Th ion using a variation of quantum logic spectroscopy, which allows for interrogating transitions where direct detection is impractical. For this, a pair of optical lattice beams generates a dipolar force [5], resulting in a motional excitation of common modes of vibration in the ion crystal which can be interrogated by the Ca+. We aim for the E1 near 402nm and the E2 392nm transition in Th+, respectively. Vortex light modes allow for shaping the laser field to specifically investigate transitions which feature mixed E/M character [6]. Taking advantage of the infrastructure of the nuclear chemistry institute and the wealth of radio-active isotopes and charge states from novel sources [7], we plan for investigation of nuclear deformations, hyperfine and isotope/isomer shifts. Last, I report the search for millicharges dark matter that benefits largely from the exquisite of ion traps [8].

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The hybrid-symmetric storage ring lattice for a high sensitivity proton EDM experiment

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The dedicated storage ring EDM, a.k.a. "frozen spin method" was born from the muon g-2 experimental method as part of the effort to increase sensitivity to the EDM of charged particles [1,2]. Over the years, further conceptual developments, high-precision simulations and lattice optimizations [3,4] led to the hybrid-symmetric storage ring design [5,6] that is both highly sensitive to EDM and functional with presently available technology. The hybrid-symmetric ring lattice essentially eliminates all known first-order systematic error sources, i.e., background magnetic fields, vertical (out-of-plane) electric fields and the residual-vertical-velocity background, all of which could have severely limited the EDM sensitivity if not addressed at the design level. It's the only known lattice that accomplishes this tall task and as such it represents a major breakthrough in the field. Our studies indicate that the statistical and systematic errors are below 10^{-29} *e*-cm level, probing new physics at hundreds of TeV mass-scale, while enhancing the sensitivity to θ_{QCD} by more than three orders of magnitude from present limits.
In addition, the experiment can directly probe dark matter and dark energy with high sensitivity [7-9] even in parasitic mode, i.e., without affecting the main experimental goals.

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Low energy particle physics experiments at PSI in the lepton sector

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Despite the immense success of the Standard Model (SM), it is well known to be incomplete in describing Nature. Most obviously it is not incorporating gravity, and also falling short in explaining cosmological observations like the baryon asymmetry of the Universe, or the nature of dark matter and dark energy. In the recent years, tensions within the SM as well arose, especially concerning lepton universality with the latest result from LHCb [1], or from the muon g-2 experiment [2].

In this talk, precision particle physics efforts at the Paul Scherrer Institute (PSI) are introduced in the lepton sector, with the focus on two novel experiments, both exploring beyond-SM physics, but using rather different methods and physics processes.

PIONEER is a newly formed international collaboration, where we are searching for potential violations of lepton flavor universality by investigating branching ratios of the charged pion decay to electrons against to muons, a number precisely predicted by the Standard Model [3].

In the LEMING experiment we aspire to carry out next generation atomic physics and gravity experiments using muonium, which is an exotic atom consisting of a muon and an electron ($M = \mu^+ + e^-$) [4]. We started this challenging task by developing a novel cold atomic M beam in vacuum using muon conversion in superfluid helium. The new tantalizing results with the cold M beam production put us on a path for increased precision in 1S-2S laser spectroscopy of M, and may pave the way for a free fall experiment, that would be the first direct measurement of the gravitational interaction using (anti-)leptons.

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Matter-antimatter pair plasmas: a new frontier in plasma physics

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In conventional plasmas (composed of electrons and ions), that the positively charged particles are significantly more massive than the negatively charged particles results in a separation of the characteristic length scales and time scales for the dynamics of the two species. This asymmetry is a key aspect of many of the complex behaviors of plasma systems. More than four decades ago, the concept of a "pair plasma", in which positively and negatively charged species have identical mass, was proposed [1]. Since then, there have been many theoretical and numerical investigations of how the collective behavior of such an unusually symmetric plasma is expected to compare to that of conventional plasmas. Among these, e.g., is a prediction for strongly magnetized pair plasmas in well-chosen magnetic geometries to possess "remarkable stability" to modes that drive turbulent transport in electron-ion plasmas [2]. Experimentally testing such predictions --- in essence, making pioneering measurements of the "hydrogen atom of plasma physics" --- is a compelling fundamental physics objective.

Toward this end, the goal of the APEX (A Positron Electron eXperiment) Collaboration is to create and study magnetically confined electron-positron pair plasmas in the laboratory. In order to achieve this, we are bringing together and further developing tools, techniques, and resources from a variety of fields. The source of our positrons is a world-class, reactor-based beam (the NEutron-induced POsitron source MUniCh). The positrons will then be collected, cooled, and accumulated to increasing numbers and densities in a series of non-neutral traps (a two-stage buffer-gas trap, a separate accumulator stage, and then a high-field, multi-cell trap). The resulting tailorable pulses will then be injected into either of two toroidal magnetic confinement devices (a levitated dipole and an optimized stellarator). This talk will provide an overview of the collaboration's recent progress [e.g., 3, 4] and upcoming milestones en route to pair plasma studies.

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Storage Rings: From Hadron Physics to Precision Measurements

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The COoler SYnchrotron (COSY) storage ring at the Institute for Nuclear Physics of Forschungszentrum Jülich (Germany) has been used with unpolarized and polarized proton and deuteron beams for hadron physics experiments between the early 1990´s and 2016 [1]. Since about 2010, the JEDI (Jülich Electric Dipole moment Investigations) collaboration has started to exploit COSY for R&D with the objective to conveive and eventually build a high-precision storage ring in order to search for charged-particle EDMs with unprecedented sensitivity. Within an ERC Advanced Grant [2] of the European Research Council, a number of significant milestones have been achieved, most notably a first direct EDM measurement for the deuteron. Since COSY is a conventional ring with magnetic deflection and focusing elements, it will not be able to reach very high sensitivity – this can only be accomplished with a dedicated charged-particle EDM ring. The degree of maturity of such a facility has recently been summarized in a publication by the CPEDM (Charged-particle EDM) collaboration [3]. The present contribution will cover the COSY achievements and the further strategy of CPEDM towards a final ring.

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Nuclear polarization effects in atoms and ions

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Precision isotope shift spectroscopy offers an opportunity to search for new physics by means of measuring King plot (KP) nonlinearities. However, KP nonlinearities might arise from standard-model effects as well, thus obscuring possible new-physics signal. One of such effects is the variation of nuclear polarizabilities between isotopes. Even though this effect is estimated to be relatively small and not the leading contribution to KP nonlinearity, it should not be overlooked in the interpretation of the data. In our work, we calculated energy-level shifts due to electric-dipole and -quadrupole nuclear polarization for 1s, 2s, 2p1/2 states in hydrogenlike ions, and for high-ns valence states in neutral atoms with $Z \geq 20$. We fit the results with elementary functions of nuclear parameters and derive a set of effective potentials which may be used to calculate polarization energy-level shifts in many-electron atoms and ions.

Muonic atom spectroscopy with radioactive targets

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An ongoing effort at the Paul Scherrer Institute towards the measurement of the nuclear charge radii of radioactive elements such as Ra-226 – needed as input for a measurement of atomic parity violation – and Cm-248 using muonic atoms is pursued by the muX collaboration. A muonic atom is typically formed when a negatively charged muon stops and is captured in an ordinary atom. The muon cascades down the atomic levels emitting characteristic X-rays. Due to the muon's larger binding energies, the low-lying muonic energy levels are highly affected by the details of the nuclear structure. Therefore, the measurement of the muonic X-rays serves as a sensitive probe of nuclear properties such as the charge radius. As a result of exploiting this method, the muX collaboration extracted the spectroscopic quadrupole moments of the stable Re-185 and Re-187 isotopes [1]. Ongoing work involves the determination of the rhenium nuclear charge radii from the analysis of their 2p-1s hyperfine muonic transitions. Stopping muons directly in radioactive targets is not possible due to their usage in the experimental area being restricted to microgram quantities. A technique to transfer muons to microgram targets has been developed by the muX collaboration employing muon transfer reactions in a high-pressure cell with a 100 bar D2/H2 gas mixture [2]. Measurements with Ra-226 and Cm-248 were performed in 2019 and are currently being analyzed. The status of the muX experiment and the future plans are presented in this contribution.

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In-beam hyperfine spectroscopy of (anti-)hydrogen

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Cold antihydrogen, the bound state of an antiproton and a positron, has first been created in 2012 at the Antiproton Decelerator of CERN. The primary interest in antihydrogen comes from the fact that its properties can be compared to ordinary hydrogen, which is one of the best studied atoms experimentally, in order to test the fundamental CPT symmetry which is one of the cornerstones of the Standard Model of particle physics. Among the two best-known transitions in hydrogen is the ground-state hyperfine transition ν_{HF} with a relative precision of better than 10^{-12}.

The ASACUSA collaboration has proposed a measurement of ν_{HF} in a beam, which allows to perform the experiment in a region far away from the strong magnetic fields needed for antihydrogen creation. The current status of creating a polarized beam of antihydrogen will be described, and the prospects of a measurement of ν_{HF}.

Initially with the aim to establish the in-beam method, ASACUSA has performed a measurement of ν_{HF} of ordinary hydrogen using a polarized beam and the same Rabi spectroscopy setup as will be used for antihydrogen and obtained a precision of 2.7 ppb [1]. Within the Standard Model Extension (SME) framework, that describes potential Lorentz invariance and CPT violation scenarios, also measurements using ordinary atoms can be used to constrain SME coefficients [2]. Experiments are ongoing to measure the orientation dependence of the static magnetic field for hydrogen hyperfine measurements [3], and the hyperfine structure of deuterium.

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Quantum system engineering and sensing for fundamental physics

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Precise engineering of quantum states of matter and control of atomic interactions provide powerful platforms to observe novel quantum dynamics and advance the precision measurement frontier. This development, together with innovative laser technology, has greatly enhanced the performance of atomic clocks, providing new opportunities to explore emerging phenomena, test fundamental symmetry, and search for new physics. I will highlight recent work on tuning atomic interactions to facilitate the measurement of the gravitation red shift at the sub-millimeter level.

Lattice clock based on molecular vibrations

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Quantum control of atoms and molecules has opened the door to using these microscopic systems in high-precision measurements and fundamental physics. In particular, diatomic molecules can now be manipulated nearly at the level of atoms. At the same time, molecules feature internal structure which is absent in atoms, such as vibrations. Here we present a precise quantum clock based on ultracold neutral molecules in an optical trap, where long-lived vibrational levels in the ground electronic potential serve as clock states [1,2,3]. The metrological properties of this clock are investigated in detail. Furthermore, we explore the application of state-of-the-art quantum chemistry to this experimental system and describe how the clock can be used to sample possible new mass-dependent forces in the nanometer range.

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Axion Quark Nuggets and Matter-Antimatter asymmetry as two sides of the same coin: theory, observations and future experimental searches

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In this talk I want to discuss the (unorthodox) scenario when the baryogenesis is replaced by a charge segregation process in which the global baryon number of the Universe remains zero. In this, the so-called axion quark nugget (AQN) dark matter model the unobserved antibaryons come to comprise the dark matter in the form of dense nuggets. In this framework, both types of matter (dark and visible) have the same QCD origin, form at the same QCD epoch, and both proportional to one and the same fundamental dimensional parameter of the system, which explains how the two, naively distinct, problems could be intimately related, and could be solved simultaneously within the same framework. I specifically focus on several recent papers written with AMO (Atomic-Molecular-Optic), Nuclear physics and Astro-physics people to apply these generic ideas to several recent proposals: 1. on broadband strategy in the axion searches; 2. on observed puzzling excess of the galactic UV radiation; 3. on recently detected Mysterious SkyQuake event.

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Laser-Microwave Double-Resonance Spectroscopy to Perform g-factor Measurements of Heavy, Highly Charged Ions at ARTEMIS in HITRAP

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In **ARTEMIS** (**A**symmet**R**ic **T**rap for measurement of **E**lectron **M**agnetic moment in **I**on**S**) [1], at **HITRAP**, we aim to perform the g-factor measurements of medium to heavy highly charged ions, such as $^{209}Bi^{82+}$. It serves as a test of QED in strong fields and we do this using laser-microwave double-resonance spectroscopy [2] in our cryogenic Penning trap facility at Darmstadt.

Currently, we have completed the final adjustments of attaching the cold valve to ARTEMIS which connects the experiment to the EBIT ion sources and the HITRAP facility. Alongside this, in-situ production and analysis of Ar^{13+} ions have been successfully carried out (currently up to a few weeks' storage time [3]). This uses the interaction of the induced current from the cold ions with the effective resistance offered by the LC-detection system made of copper/NbTi resonators to non-destructively detect the ions. Most recently, we have successfully managed to receive and store ions from an offline ion source and are well on our way to the first measurements with heavy, highly charged ions at our confirmed beamtime of May 2022.

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Electron EDM measurement with caesium in argon matrix

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Electric Dipole Moments (EDM) are sensitive probes for physics beyond the Standard Model. The EDM with Atoms and Molecules in Matrix (EDMMA) project is a collaboration between Laboratoire Aimé Cotton (LAC) and Institut des Sciences Moléculaires d'Orsay (ISMO) for the experiments, Laboratoire de Physique des Lasers (LPL) for its expertise in metrology and precision measurements, and Centre de recherche sur les Ions, les MAtériaux et la Photonique (CIMAP) for the theoretical analysis. We propose to improve on the sensitivity of extant electron EDM measurements by using caesium atoms embedded in a cryogenic solid matrix of inert gas or hydrogen, which would increase the electron density and coherence time.

I will present the design of an experimental setup for preliminary spectroscopic study of caesium in argon, including the cryostat, the deposit rate monitoring by interferometry, the absorption and fluorescence spectrometry, and the magnetic field implementation. Some results are also available : the interpretation of early absorption and fluorescence spectral data of caesium, and a model for the optical quality of the matrix.

Probing the axion gradient-coupling with nuclear magnetic resonance spectroscopy

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The cosmic axion spin precession experiment (CASPEr) is a nuclear magnetic resonance (NMR) experiment to search for axion and axion-like particles (ALPs) that possibly make up a significant portion of dark matter in the Universe [1]. The current CASPEr-gradient setup in Mainz is an NMR spectrometer built specifically for the frequency range 100 Hz to 4.2 MHz, corresponding to ALP masses of approximately 10^{-13} to 10^{-8} eV. We will present results from the commissioning phase of the setup, where we aim to detect the spin-projection noise of a sample of thermally polarized protons. Recently, we showed how this noise source together with thermal and amplifier noise is expected to present itself in our search for ALPs [2]. Furthermore, we will discuss our recent work on the predicted line-shape of the ALP signal as well as expected daily and yearly modulations [3].

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LIONTRAP: Towards High-Precision Mass Measurements of the Helium-3 and Tritium Nuclei

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LIONTRAP is a Penning trap mass spectrometer, optimized for measuring atomic masses of light ions with a relative precision of a few parts per trillion (ppt). Ultra-precise measurements of the rest masses of the proton, deuteron, alpha particle, as well as the tritium and helium-3 nuclei, together with the electron rest mass, serve as essential parameters for sensitive tests of fundamental physics. For example, the tritium and helium-3 mass difference is used as a consistency check for the model of systematics used by the KATRIN experiment [1].
The mass values of the lightest ions are interlinked and allow redundancy checks. The most precise mass measurements performed by different groups revealed an inconsistency of about 5 standard deviations, which is also known as "light ion mass puzzle". In order to resolve this puzzle, LIONTRAP measured the masses of the proton [2], the deuteron and the HD+ molecular ion [3], which are consistent with the values reported by FSU [4]. However, the inconsistency of about 3 standard deviations remains when these values are combined with the literature mass value of the helium-3 nucleus, which suggests motivation for an independent measurement of the mass of helium-3.
In the next steps, LIONTRAP aims at measurements of the helium-3 and tritium nuclei masses with a relative uncertainty better than 10 ppt. In this contribution the current status of the experiment is reviewed, including the helium-3 source preparation for the upcoming mass measurement campaign and modifications of the trap stack for incorporating a radioactive tritium source.

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Precision Measurements with Trapped Ion Atomic Clocks at the Lifetime and Systematic Limit

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Trapped ion atomic clocks have recently demonstrated systematic uncertainties down below the 10^-18 level while also showing that new spectroscopy techniques can be used to perform high stability measurements limited only by the lifetime of the excited state. We present recent progress in a the latest generation Al+ ion clock and an outlook toward precision measurements we aim to perform at the lifetime limit, utilizing the full accuracy characterized by our upcoming systematic uncertainty evaluation.

Precision measurements with cold trapped HD+ ions for THz electric field characterization

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Doppler-free rotational spectroscopy of cold trapped HD^+ ions enabled improved precision and record-high resolution in the terahertz domain [1]. Hydrogen molecular ion theory allowed to predict the rovibrational energy levels with a precision beyond the 10^{-11} level, the hyperfine energy levels with 10^{-6} level precision, and various energy level shifts in external fields by accurate *ab-initio* calculations. Rydberg spectroscopy of alkali atoms enabled SI-traceable measurements, sub-wavelength resolution, accurate, stable and long-term reproducible detection of the microwave electric fields [2]. The comparison between theoretical predictions and experimental measurements for the frequency shifts induced on HD^+ transitions by external fields is discussed here in view of a new method for THz electric field sensing that is traceable to the fundamental constants and to the SI second [3,4].

Precisely, a THz-wave slightly detuned to the (v,L)=(0,0)→(0,1) transition of HD^+ may be characterized by measuring the lightshift induced on the (v,L)=(0,0)→(0,2) two-photon transition that is probed by resonance enhanced multiphoton dissociation (Fig. 1.A). Optimal Zeeman shifting of the HD^+ energy levels enables detection of weak THz electric fields at the μV/m level that is beyond the performances of microwave electrometry based on alkali vapour spectroscopy. In addition, the polarization ellipse of a THz-wave may be fully characterized from six lightshift measurements performed for three intensities and two orientations of the magnetic field in the ion trap. The Cartesian components of the electric field of a circularly polarized THz-wave (Fig. 1.B) with an intensity of 1 W/m^2 may be characterized with μV/m-level uncertainties or better for the amplitudes and mrad-level uncertainties or better for the phases.

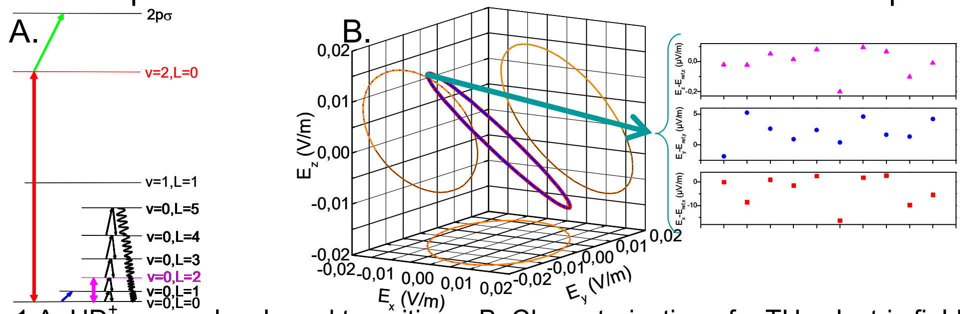

Fig. 1 A. HD^+ energy levels and transitions. B. Characterization of a THz electric field

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New tools for preparing, preserving, and detecting polarized spins

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The polarized spins of neutrons, and nuclei in closed-shell atoms, provide a sensitive and systematically clean platform to search for the signatures of CP-violating new physics. CP-violation beyond the Standard Model is required to explain the observed cosmological baryon asymmetry, and the associated new degrees of freedom often generate or enhance permanent electric dipole moments (EDMs) that could be measured in low-energy bound states [1]. These CP- and T-violating polarization moments can arise from various weak-scale interactions (including small Standard Model contributions), and precision measurements in many different systems are needed to disentangle the possible effective sources. Such measurements typically rely on time-domain interferometry with polarized spins, key systems including stored ultracold neutrons (UCN) and hyperpolarized noble gas nuclei. These examples are mainly sensitive to effective sources involving hadrons, including certain semileptonic interactions. To constrain lepton EDMs and other categories of effective sources, measurements in other systems (such as paramagnetic molecules) are also required.

Recent years have seen renewed activity in EDM searches using hyperpolarized noble gas nuclei, leading to new experimental limits [2,3]. Further advances in sensitivity will be supported by systematic studies [4], dedicated facilities, and new methods including the application of direct frequency comb spectroscopy in the deep ultraviolet to directly probe the ground-state nuclear spin projection. Applying these methods for laser cooling and optical pumping is also envisioned in the long term.

On the other hand UCN can be produced and trapped by established methods, with transverse spin-coherence times of several hundred seconds. Yet state-of-the-art experiments continue to face severe statistical limitations, even at world-leading sources [5]. Experiments inside superfluid-helium UCN sources offer higher particle densities by eliminating transport losses, and will rely on quantum sensing methods to realize spin- and energy-selective *in-situ* UCN detection with high statistics.

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Proton capture on stored radioactive ions

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By combining two unique facilities at GSI (Helmholtz Centre for Heavy Ion Research), the fragment separator FRS and the experimental storage ring ESR, the first direct measurement of a proton capture reaction of a stored radioactive isotope has been accomplished. The combination of sharp ion energy, ultra-thin internal gas target, and the ability to adjust energy in the ring enables precise, energy-differentiated measurements of the (p,λ)-cross sections. Our new results provide a sensitive method for measuring (p,λ) and (p,n) reactions relevant for nucleosynthesis processes in supernovae, which are among the most violent explosions in the universe and are not yet well understood. The cross section of the ^{118}Te(p,λ) reaction was measured at energies of astrophysical interest. The heavy ions were stored with energies of 6 and 7 MeV/nucleon and interacted with a hydrogen jet target. The produced ^{119}I ions were detected with double-sided silicon strip detectors. The radiative recombination process of the fully stripped ^{118}Te ions and electrons from the hydrogen target was used as a luminosity monitor. An overview of the experimental method and preliminary results from the ongoing analysis will be presented.

Dynamics of mixed species Coulomb crystals with highly charged ions in a superconducting Paul trap

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In a novel ion trap concept, the CryPTEx-SC experiment at the Max Planck Institute for Nuclear Physics in Heidelberg, Germany combines a linear Paul trap with a niobium superconducting radio-frequency cavity to form a quadrupole trap with ultralow-noise trapping fields [1]. The goal of the project is to perform precise frequency metrology of highly charged ions (HCIs), which are excellent candidates for the development of next-generation optical atomic clocks and sensitive probes in the search for new physics. Control and read-out of HCIs will be implemented using quantum logic spectroscopy with co-trapped Be^+ ions.

We will present the results of the first cold highly charged ions stored in our ion trap. After their production in an electron beam ion trap, the HCIs are transferred through an electrostatic beamline where they are bunched and decelerated. The HCIs are then captured in and sympathetically cooled by a Coulomb crystal of several dozen laser-cooled Be^+ ions trapped in the Paul trap beforehand. Subsequent controlled removal of Be^+ ions by exciting secular motion is used to prepare mixed species ion crystals comprising various numbers of Be^+ ions and HCIs, down to a single HCI with a single Be^+ ion, the prerequisite for quantum logic spectroscopy.

We will discuss the flexible retrapping technique which opens up an extensive range of highly charged ion species to precision studies and explore the dynamics of mixed species Coulomb crystals consisting of ions with disparate charge-to-mass ratios.

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Hadronic Vacuum Polarization Corrections in Highly Charged Ions

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The hadronic vacuum polarization correction to the energy levels and the g factor of a bound electron is investigated theoretically. An empirical hadronic polarization function obtained from measured cross sections of electron/positron annihilation into hadrons is applied to derive an effective hadronic Uehling potential. The corrections are calculated for low-lying hydrogenic levels using analytical Dirac-Coulomb wave functions, as well as with bound wave functions accounting for the finite nuclear radius. Closed formulas for the hadronic shifts in case of a point-like nucleus are derived. In heavy ions, such effects are found to be much larger than for the free-electron g factor.

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High-precision mass-ratio measurements of ytterbium isotopes and absolute mass measurement of 20Ne with the Penning-trap mass spectrometer PENTATRAP

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Measurements with the Penning-trap mass spectrometer Pentatrap [1], located at the Max-Planck-Institute for Nuclear Physics in Heidelberg, allow to determine mass ratios with a relative uncertainty in the few parts per trillion regime using highly charged ions [2]. Pentatrap's mass measurements of selected nuclides allow, among others, to contribute to tests of special relativity, bound-state quantum electrodynamics and neutrino-physics research. Achieving this level of precision requires using a cryogenic image-current detection system with single-ion phase-sensitive detection methods in combination with highly charged ions provided by external ion sources. Recent measurement results on neon for tests of bound-state quantum electrodynamics will be presented as well as measurements on stable isotopes of ytterbium for dark matter research [3].

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New Physics from the Low-Multipole Part of the CMB Spectrum

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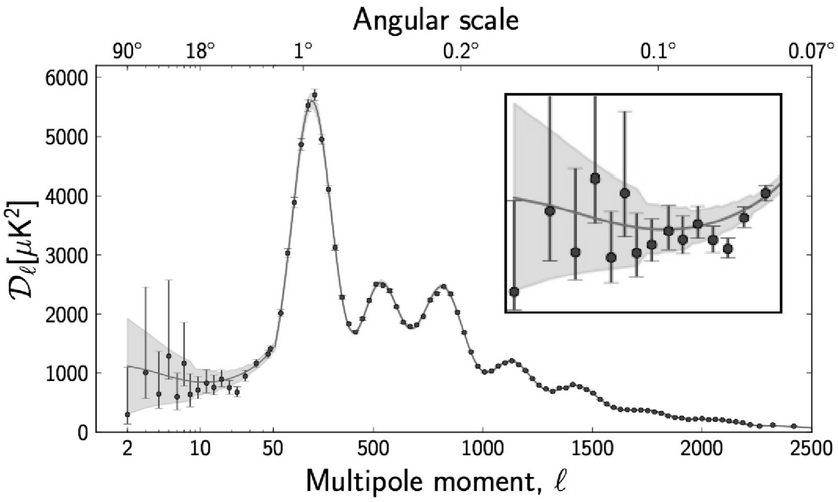
Analysis of the cosmic microwave background (CMB) spectrum became now a powerful tool for testing the cosmological models and inferring the basic cosmological parameters. However, while theoretical predictions and observational data coincide very well for the moderate and high multipoles (above a few dozens), there is a drastic disagreement in the low-multipole part of the spectrum, which exhibits the pronounced oscillations instead of being a smooth one [1].



It is the aim of the present report to show that a possible explanation of such oscillations, in principle, could be attributed to the nontrivial domain structure of vacuum [2, 3], forming after a symmetry-breaking phase transition of a Higgs-like field in the early Universe [4]. Here, we demonstrate the model spectra of perturbations resulting from the domains and confront them with the available observations. In summary, despite a lot of uncertainties, the above-mentioned hypothesis provides a reasonable explanation for the oscillatory behavior of the CMB spectrum at the large scales. Moreover, the observed characteristics of the low multipoles could be used to derive parameters of the underlying Higgs fields and, therefore, to clarify the relevant elementary-particle physics.

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Shifting lines: nuclear & atomic transitions in search for new bosons and variations in fundamental constants

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We live in the golden age of precision spectroscopic measurements determining energy transitions in atomic and nuclear systems. Theoretical estimates of such transitions catch up with the experimental efforts. This enables to find small discrepancies between the expected transition frequency and the measured one. An unexpected shift in the frequency, if cannot be accounted for by known effects or any kind of uncertainty, can be accounted for by novel effects beyond the current standard model.

New bosons, such as axionlike particles and Z' bosons, if exist, can be exchanged between the constituents of atoms, giving rise to a potential which shifts the energy levels. We explore these effects and put bounds on the coupling constants of such interactions in antiprotonic helium, muonium, positronium, helium, and hydrogen.

In nuclear systems, temporal or spatial variation of the fine structure constant α or the quark mass m_q can cause shifts in the nuclear energy levels. We determine the enhancements to such effects in Mössbauer transitions as well as in the nuclear clock transition of Thorium 229. We find a link between the enhancement of α and m_q.

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Selecting atoms and molecules tailored for robust bounds on fundamental sources of P,T-violation in a global analysis

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Physics beyond the standard model of particle physics can introduce novel mechanisms that give rise to violations of discrete symmetries, i.e. space parity (P), time-reversal (T) and charge conjugation (C). Due to internal enhancement effects heavy-elemental atoms and molecules are among the most promising candidates for a first detection of P,T-violation beyond the Standard Model [1]. However, many different fundamental sources of P,T-violation, such as hypothetical P,T-odd currents between quarks and quarks, quarks and electrons or permanent electric dipole moments (EDMs) of elementary particles, could induce net P,T-odd moments in atoms and molecules [2]. Thus, a measurement of a P,T-odd EDM of an atom or a molecule is difficult to interpret and predict due to possible interference of the various fundamental sources of P,T-violation and several good experiments are required for a global model-independent analysis of the results [3].

In this contribution all possible sources of the net P,T-odd EDM of atoms and molecules are studied within a simple qualitative electronic-structure model in terms of electronic and nuclear angular momenta and the nuclear charge number of the heaviest atom of an arbitrary linear molecule. Furthermore, the influence of nuclear structure effects [4] and effects due to the chemical enhancement [5] on the validity of the model is estimated. Finally, rules for selection of good candidates for future experiments that have the potential to reduce the coverage region in the global P,T-odd parameter space are presented.

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A Gravity Measurement of Antihydrogen

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Since 2010, when antihydrogen was trapped for the first time [1], the ALPHA collaboration has pioneered measurements of antihydrogen. The newest addition to the ALPHA experiment is the ALPHA-g apparatus, which has the purpose of measuring how antihydrogen falls in the gravitational field of the Earth. This test of CPT and the Free Fall Weak Equivalence Principle is done by trapping cold antihydrogen in a vertical magnetic minimum trap and letting it escape in the up/down direction. This poster explains the details of the magnet configuration and the intended measurement scheme.

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Observation of Anisotropic *Zitterbewegung* in Non-Abelian Gauge Field

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We experimentally observe *Zitterbewegung* in a two-dimensional degenerate Fermi gas, in the presence of a synthetic non-Abelian gauge field. Despite the fact that the original proposal of *Zitterbewegung*, by Schrodinger, did not have any requirement on the non-Abelian nature of the gauge field, we show that to observe anisotropic *Zitterbewegung*, the non-Abelian nature of the gauge field is an essential ingredient. In our experiments, we reveal the anisotropic nature of *Zitterbewegung*, namely, the direction-dependence of the oscillation-amplitude and the frequency of oscillation. To observe these effects, we leverage the momentum-dependence of the energy eigenstates, by introducing a kick to the atomic wave packet. Complete suppression of the *Zitterbewegung* is observed at special angles in momentum-space, and this phenomenon is understood with the spin texture of this spin-orbit coupled system. The role of Fermi degeneracy is manifested in the damping of the oscillation.

Towards intra-cavity nonlinear laser excitation of the thorium-229 isomeric state

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The combination of a near-infrared frequency comb with femtosecond pulses and a suitable enhancement cavity allows us to reach peak intensities of up to $10^{14}\mathrm{W/cm^2}$ at a repetition rate of 100 MHz. Consequently, we can investigate processes with low cross-sections in experimentally manageable acquisition times. An intra-cavity velocity map imaging (VMI) spectrometer at the focus region collects energy spectra of ionized electrons. As the cavity is designed to be polarization insensitive, polarization shaping of the incoming pulses allows tomographic reconstruction of photoelectron angular distributions. Furthermore, pulses are fed from both directions in the ring cavity with an additional interferometer in one direction permitting studies of strong field effects in standing waves and versatile pump-probe experiments.
An interesting target is the isotope thorium-229 because of the uniquely low energy of 8 eV [1] of the first excited nuclear state. Due to the long radiative lifetime, this narrow transition could be the basis of a nuclear optical clock [2], which promises high accuracy and potentially high sensitivity to the variation of fundamental constants. Up to now, the very large uncertainty of the transition energy in the order of 0.1 eV hinders the development of a suitable laser system in the VUV and no direct excitation of the isomer has been demonstrated so far. We propose a technique for non-linear excitation of the thorium-229 nucleus in a femtosecond enhancement cavity. Successful excitation will result in emission of internal conversion electrons, which can be detected for direct frequency comb spectroscopy of the nuclear transition.

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Physics of laser-assisted nuclear processes as the base for creation of the nuclear clock

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It is tempting to use laser for manipulations with the nuclear processes. Nuclear decay can be enhanced considerably by making use of a resonance with the electronic transitions, which can be further tuned either through changing the electron shell, or irradiating with resonance field of a laser [1]. Thus, it was predicted that the decay of the ^{229}Th isomer would be by ~700 times faster in the hydrogen-like ions due to isomer and ground-state spin mixing. The lifetime of the nucleus in the crystal matrix also may vary. Moreover, experiments show the electronic shell effects on the beta decay. And effect of the electronic shake on the double *e*-capture diminishes the lifetimes of the parent nuclei by several times. There is a comparative study of α decay in H-, He-like ions on the urgent agenda, with respect to that in neutral atoms.

The resonance properties of the electron shell are of extreme importance for creation of the nuclear clock. From the other side, it is generally accepted that the nuclear properties, specifically the radioactive decay constant, are essentially independent of the physical environment. Such stability against the environmental medium underlies the idea of the nuclear clock. This is in contrast with what is said above. In fact, in the case of the nuclear deexcitation through the resonance conversion (or electronic bridge), the decay probability turns out to be directly proportional to the atomic width. Therefore, it may be mastered by simple factors, such as ambient temperature and atmospheric pressure. This dependence may be directly related to the thorium puzzle of the short lifetime in the single ions [2]. Especial features of the electronic-nuclear resonance are discussed.

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Towards the first demonstration of gravitational quantum states of atoms with a cryogenic hydrogen beam

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Abstract

At very low energies, an atom above a horizontal surface can experience quantum reflection due to the attractive Casimir-Polder potential. The quantum reflection holds the atom against gravity and leads to quantum gravitational states (GQS), in analogy to what has been observed with ultracold neutrons [1]. The GRASIAN-collaboration pursues the first measurement of GQS of atomic hydrogen. For this purpose, an experiment has been designed and set up at ETH Zurich. In the past year, a cryogenic hydrogen-beam and a pulsed ultraviolet laser detection system were installed and characterized. The interaction region, where the actual GQS-measurement will be performed, is currently being installed.

The use of hydrogen is not only motivated by the fact, that GQS have never been observed with atoms. The enhanced statistics available through the use of hydrogen atoms (versus ultracold neutrons) will increase the sensitivity to deviations from Newtonian Gravity. For instance, short-range forces predicted in extensions of the Standard Model would alter the GQS, and would hence be detectable by a high-precision GQS-measurement.

Additionally, the measurement of GQS of hydrogen will serve as a benchmark demonstration for the measurement of gravitational properties of Antihydrogen. Furthermore, the extremely low velocities of atoms in GQS also promise improved accuracies in precision laser and microwave spectroscopy.

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Hyperfine Spectroscopy of Single Molecular Hydrogen Ions in a Penning Trap at Alphatrap

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With only a single bound electron, molecular hydrogen ions are the simplest molecules available and are thus an excellent system for testing quantum electrodynamics by comparing experiments and theory. We have initiated a program on high-precision spectroscopy on single hydrogen molecular ions in the Penning-trap setup of ALPHATRAP [1] utilizing the continuous Stern-Gerlach effect for state detection [2]. Initially, we will focus on the hyperfine structure of the HD^+ ion in the microwave regime. This will allow extracting the bound g factors of the constituent particles and coefficients of the hyperfine hamiltonian. The latter can be compared with high-precision ab initio theory and are important for a better understanding of rovibrational spectroscopy performed on this ion species [3].
In the future, we aim to extend our methods to single-ion rovibrational laser spectroscopy of H_2^+ at infrared wavelengths enabling the ultra precise determination of fundamental constants such as the proton-to-electron mass ratio [4]. The development of the required techniques for this measurement will be an important step towards spectroscopy of an antimatter $\overline{H_2^-}$ ion for tests of matter-antimatter symmetry [5].
In this contribution, I will present an overview of the experimental setup and first measurement results of microwave spectroscopy of the ground-state hyperfine structure of HD^+.

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Direct high precision measurement of the Q-value of the electron capture in ^{163}Ho and metastable states in highly charged ions

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The high-precision Penning-trap mass spectrometer Pentatrap [1] features a stack of five Penning traps and determines mass-ratios with a relative uncertainty below 10 ppt. Mass-ratio determinations of stable and long-lived highly charged ions have numerous applications, among others, in neutrino physics [2] and the search of possible clock transitions in highly charged ions (HCI) [3]. The unique features of Pentatrap include access to HCI, a stable 7 T magnet, and a cryogenic detection system with single ion phase sensitivity. The latest measurements include the Q value of the beta-decay of ^{163}Ho with a relative uncertainty of below 7 ppt and the mass of ^{208}Pb. In lead a long-lived metastable electronic state was discovered.

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First results towards a measurement of the electron EDM in a cryogenic matrix

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EDMs, i.e. electric dipole moments of elementary and composited particles are predicted by a wide range of theories beyond the standard model. To this day, experiments could only give upper boundaries for the different EDMs which nonetheless provided valuable input in limiting parameter spaces and rejecting theories.

In the present project, we propose to perform a measurement of the electron EDM through alkali atoms embedded in a cryogenic noble gas matrix. Compared to current experiments, matrices offer much higher sample sizes while still maintaining the characteristics of an atomic physics experiment. We present first tests on a caesium doped argon matrix.

Measuring Gravity with VLBAI

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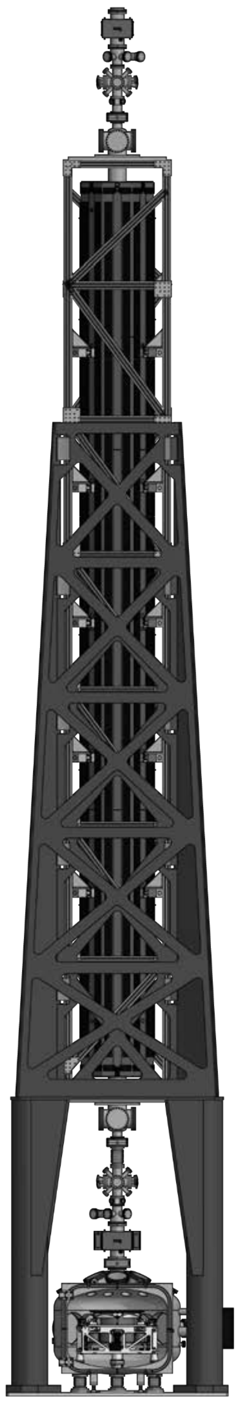
We discuss the basic principles of the 16m **V**ery **L**arge **B**aseline **A**tomic **I**nterferometry (VLBAI) facility where UFF and UGR postulates can be tested through matter-wave interferometry [1] by exploiting the linear scaling of acceleration sensitivity with the free fall distance. We show the VLBAI setup and environment which includes a magnetically shielded baseline, a seismic attenuation system and discuss the sources of gravity gradients around it. We take a look at the Yb setup for generating a high-flux atomic source delivering 1 x 10^9 atom/s into the 3D MOT and the laser cooling techniques for producing ultra-cold atoms necessary for our applications [2,3].



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Precision spectroscopy of the 2S-6P transition in atomic hydrogen

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Precision spectroscopy of atomic hydrogen is an important way to test bound-state quantum electrodynamics (QED), one of the building blocks of the Standard Model. In its simplest form, such a test consists of the comparison of a measured transition frequency with its QED prediction, which can be calculated with very high precision for the hydrogen atom. However, these calculations require some input in the form of physical constants, such as the Rydberg constant and the proton radius, both of which are currently determined to a large degree by hydrogen spectroscopy itself. Therefore, the frequency of at least three different transitions needs to be measured in order to test QED.

To this end, we have previously measured the 2S-4P transition frequency with a relative uncertainty of 4 parts in 10^{12} [1]. In combination with the very precisely known 1S-2S transition frequency [2], this allowed the most precise determination of the Rydberg constant and the proton radius from atomic hydrogen. Good agreement was found with the much more precise value of the proton radius extracted from spectroscopy of muonic hydrogen, which had been in significant disagreement with previous data from hydrogen. However, a new measurement of the 2S-8D transition [3] is again in disagreement, highlighting the need for further and more precise studies of different transitions.

Recently, we have probed the 2S-6P transition, which has a three times lower linewidth compared to the 2S-4P transition. This factor, together with other experimental improvements [4], allows for a five-fold improvement in fractional precision and in the determination of the Rydberg constant and the proton radius, and a test of QED on the level of 1 part in 10^{13}. Here, I will discuss the ongoing data analysis and present preliminary results.

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Towards Ramsey-Comb Spectroscopy of Hydrogen-like Helium

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The 1S-2S transition of hydrogenic systems is a benchmark for tests of fundamental physics [1]. A prominent example is the 1S-2S transition in atomic hydrogen, which has been measured with a relative uncertainty of 10^-15 [2]. This impressive measurement has proven very difficult to improve upon, in part due to the difficulty of controlling systematic uncertainties below 10^-15 in an atomic beam experiment. On the theory side, fundamental physics tests are currently hampered by estimates of uncalculated higher-order QED terms and the uncertainties in the fundamental constants required for their calculation [3].

Our approach to address these challenges is to measure the 1S-2S transition of hydrogen-like helium (He+), which can be trapped and sympathetically cooled. With twice the nuclear charge of hydrogen, certain interesting QED contributions are strongly enhanced. In addition, nuclear properties, e.g. the alpha particle charge radius, can be probed [3].

We want to measure the extreme ultraviolet 2-photon 1S-2S transition in He+ via Ramsey-comb spectroscopy (RCS) [4]. RCS uses two amplified and up-converted pulses of a frequency comb to perform a Ramsey-like excitation. We will excite the two-photon transition with a fundamental photon at 790nm and its 25th harmonic at 32nm. The He+ is confined in a Paul trap and sympathetically cooled by a Be+. Successful excitation is detected via a quantum logic [5] type read-out scheme.The many components required for the He+ experiment are approaching completion and we will report on their current status. Using the RCS method we aim to do a first 1S-2S measurement of He+ with an accuracy of 10 kHz, while an accuracy of better than 50 Hz should be ultimately achievable.

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Ab initio quantum theory of mass defect and time dilation in trapped-ion optical clocks

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We derive a Hamiltonian for the external and internal dynamics of an electromagnetically bound, charged two-particle system in external electromagnetic and gravitational fields, including leading order relativistic corrections. We apply this Hamiltonian to describe the relativistic coupling of the external and internal dynamics of cold ions in Paul traps, including the effects of micromotion, excess micromotion and trap imperfections. This provides a systematic and fully quantum mechanical treatment of relativistic frequency shifts in atomic clocks based on single trapped ions. Our approach reproduces well known formulas for the second order Doppler shift for thermal states, which were previously derived on the basis of semi-classical arguments. We complement and clarify recent discussions in the literature on the role of time dilation and mass defect in ion clocks.

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Stringent Tests of QED by Measuring Bound-Electron g Factors in Highly Charged Tin

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Highly charged ions are a great platform to test fundamental physics in strong electric fields. The field strength experienced by a single electron bound to a high-*Z* nucleus reaches strengths exceeding 10^{16}V/cm. Perturbed by the strong field, the g factor of a bound electron is a sensitive tool that can be both calculated and measured to high accuracy. In the recent past, *g*-factor measurements of low-*Z* ions reached precisions below 5 10^{-11}. Following this route, the ALPHATRAP Penning trap setup is dedicated to precisely measure bound-electron *g* factors of the heaviest highly charged ions.

In this contribution, our recent measurement of bound-electron *g* factors in highly charged tin will be presented. Over the course of multiple months, *g* factors for three different charge states have been measured, each allowing a unique test of QED in a heavy highly charged ion, probing different *g*-factor contributions. Furthermore, progress on a new EBIT setup is presented. This will eventually allow ALPHATRAP in the future to inject and measure even heavier highly charged systems beyond hydrogenlike lead (Pb^{81+}) in our Penning-trap apparatus.

An XUV frequency comb for precision spectroscopy of highly charged ions

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Highly charged ions (HCI) have been proposed as extremely sensitive probes for New Physics beyond the Standard Model and as novel frequency standards, due to their insensitivity to external fields [1]. To perform precision spectroscopy of cold HCI in the extreme ultraviolet (XUV), we have built an XUV frequency comb by transferring the coherence and stability of a near-infrared frequency comb to the XUV by means of high-harmonic generation [2, 3]. Amplified femtosecond pulses from a 100 MHz near-infrared frequency comb are fed into an astigmatism-compensated femtosecond enhancement cavity inside an ultra-high vacuum chamber. In this cavity, consecutive pulses are coherently superimposed and intensities of 10^{14} W/cm² are reached in the focus region.
High harmonics up to the 35th order (corresponding to 42 eV; 30 nm) are generated inside a gas jet and coupled out of the cavity [4]. This XUV light will be guided to trapped and sympathetically cooled HCI [5, 6] in a superconducting Paul trap to perform direct XUV frequency comb spectroscopy [7].

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New-physics contributions and “photon-bridge” effects to the energy levels in simple ions

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The influence of hypothetical new interactions beyond the standard model on atomic spectra has attracted recent interest. In the present work, interelectronic photon exchange corrections and radiative quantum electrodynamic corrections to the hypothetical contribution to the energy levels of few-electron ions from a new interaction are calculated. The ground states of H-like, Li-like, and B-like ions are considered, as motivated by proposals to use isotope shift spectroscopy of few-electron ions in order to set stringent constraints on hypothetical new interactions. It is shown that, for light Li-like and B-like ions, photon-exchange corrections are comparable to or even larger than, by up to several orders of magnitude, the leading one-electron contribution from the new interaction, when the latter is mediated by heavy bosons.

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High-Resolution Measurement of X-Ray Transitions in He-like Uranium at CRYRING@ESR

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Recent developments regarding metallic magnetic calorimeters (MMCs) have resulted in a new class of detectors for precision X-ray spectroscopy, for example the maXs detectors [1] (cryogenic micro-calorimeter arrays for high resolution X-ray spectroscopy). Outstanding features of MMCs are the combination of a very high energy resolution comparable to crystal spectrometers with the broad bandwidth acceptance of semiconductor detectors. These detectors are based on the following measurement principle: The energy deposition of an incident X-ray photon leads to a measurable temperature rise of an absorber. At operation temperatures below 50 mK this leads to a change in the magnetisation of a paramagnetic sensor which can be measured by a superconducting quantum interference device (SQUID) [2]. The ^{229}Th isomeric energy has recently been determined with unprecedented precision [3] demonstrating the outstanding capabilities for precision x-ray spectroscopy.

In this contribution we present the first application of maXs-type detectors for high resolution x-ray spectroscopy at CRYRING@ESR. Two maXs detectors were placed at angles of 0° and 180° with respect to the ion beam axis at the electron cooler. Within the experiment, X-ray radiation emitted as a result of recombination events between the electron cooler electrons and a stored beam of U^{91+} ions was studied.

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Towards Quantum Logic Spectroscopy of Single Molecular Ions

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High precision spectroscopy of trapped molecular ions constitutes a promising tool for the study of fundamental physics. Possible applications include the search for a variation of fundamental constants and measurement of the electric dipole moment of the electron. Compared to atoms, molecules offer a rich level structure, permanent dipole moment and large internal electric fields, which make them exceptionally well suited for those applications. However, the additional rotational and vibrational degrees of freedom result in a dense level structure and absence of closed cycling transitions. Therefore, standard techniques for cooling, optical pumping and state detection cannot be applied. This challenge can be overcome by quantum logic spectroscopy [1]. In addition to the molecular ion, a well-controllable atomic ion is co-trapped, coupling strongly to the molecule via Coulomb interaction. The shared motional state can be used as a bus to transfer information about the internal state of the molecular ion to the atomic ion, where it can be read out using fuorescence detection [2]. Here, we present the status of our experiment, developing quantum logic protocols for high precision spectroscopy using calcium as the logic ion. Our experimental setup was designed to be well-suited for the spectroscopy of a wide range of molecular species including hydrides or homonuclear molecular ions [3]. Following the approach of Chou et al. [4] for CaH+, we are setting up a far detuned Raman laser setup for the purpose of Zeeman state preparation and rotational state detection of MgH+. We will further extend the scheme by using bichromatic Raman interactions that will allow more versatile quantum operations on the molecular ions. The anticipated level of control will allow us to spectroscopically determine molecular properties such as the nuclear spin-rotation coupling constant.

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Parity-Violation Studies with Partially Stripped Ions

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We present a theoretical study of photoexcitation of highly charged ions from their ground states, a process which can be realized at the Gamma Factory at CERN. The focus lies on the question of how the excitation rates are affected by the mixing of opposite-parity ionic levels. This mixture arises due to an external electric field and the weak interaction between electrons and the nucleus. In order to reinvestigate this “Stark-plus-weak-interaction” mixing, well-known in neutral atomic systems, we employ relativistic Dirac theory. Based on the developed approach, detailed calculations are performed for transitions in hydrogen- and lithium-like ions. In particular, we focus on the difference between the excitation rates obtained for right- and left-circularly polarized incident light. This difference is induced by the mixing of opposite-parity ionic levels and is usually characterized in terms of the circular–dichroism parameter. We argue that future measurements of circular dichroism, performed with highly charged ions in the SPS or LHC rings, may provide valuable information on the electron–nucleus weak–interaction coupling.

muEDM: Search for the muon EDM using the frozen-spin technique at PSI

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We prepare the first dedicated search for the permanent electric dipole moment (EDM) of the muon employing the frozen-spin technique at the Paul Scherrer Institute (PSI), Switzerland [1]. The muEDM experiment aims for a sensitivity of better than 6 x 10^(-23) e.cm, more than three orders of magnitude improvement on the current best limit set by the E821 experiment at the Brookhaven National Laboratory. The muon EDM is a unique probe to search for additional sources of CP violation beyond the CP violating phase of the Cabibbo-Kobayashi-Maskawa matrix in the Standard Model of particle physics. Any detection of a non-zero EDM at the current experimental sensitivity would invoke new sources of CP violation, generally abundant in many theories beyond the SM (BSM). In particular, the recently reported 4.2σ discrepancy in the muon g−2 as well as the observed tensions in *B*-decays motivate BSM concepts which allow a larger muon EDM without tight constraints from the existing limit on the electron EDM. This makes the dedicated muon EDM search very attractive to further push EDM searches beyond the first generation fundamental particles and to explore the role of the lepton flavour universality. I will report on R&D studies performed at PSI in preparation for a dedicated high precision measurement of the muon EDM. I will focus on the characterisation of possible beamlines to host the experiment and the measurement of multiple Coulomb scattering of positrons at low momenta for the detector and electrode design of the experiment.

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High-precision determination of the atomic mass of Helium-4

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Atomic masses with high precision can be obtained by Penning-trap mass spectrometry. The LIONTRAP experiment is one such high-precision mass spectrometer that can achieve relative mass uncertainties of the order of 10^{-11} and is dedicated to light ions. However, the relatively large ratio of kinetic energies compared to the low rest masses makes measuring the masses of light ions especially challenging. The rest masses of many light nuclei, e.g., the proton and the deuteron are of great importance for testing our current understanding of physics as well as in metrology.

The results at LIONTRAP include the atomic mass measurements of the proton [1], the deuteron and the HD^+ molecular ion [2]. The deuteron mass was measured to a relative precision of 8.5 ppt [2]. Our results show an excellent agreement with values that were extracted from laser spectroscopy of HD^+ [3]. This comparison is currently limited by the precision of the electron's mass in atomic mass units (amu), derived from a measurement of the bound electron g-factor in $^{12}C^{5+}$ [4]. Helium-4 is a prime candidate for a future improvement, as it is far less sensitive to higher-order terms of quantum electrodynamics (QED) and to the charge radius of the nucleus. Currently, we are measuring the mass of Helium-4 nucleus to support such a determination of the electron mass in amu. In this contribution, the present status and results of the experiment will be discussed.

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Two-loop self-energy correction to the bound-electron g-factor: update M-term

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In heavy hydrogenlike ions, the theoretical uncertainty of the bound-electron g-factor is dominated by uncalculated two-loop Feynman diagrams. Partial results for the two-loop self-energy correction to the g-factor were presented in our previous work [1]. In this work, we present our results for the so-called M-term contribution to the two-loop self-energy correction. This corresponds to the ultraviolet finite part of nested and overlapping loop diagrams in which the Coulomb interaction in intermediate states is taken into account exactly. This work is an important step towards improving the theoretical accuracy of the g-factor in the high-Z regime. Our results are highly relevant for ongoing and future QED tests, the determination of fundamental constants and the search for new physics with heavy ions [2].

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Gauge invariant subsets in two-photon-exchange diagrams resulting from a redefined vacuum approach

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Within bound-state QED, the interelectronic interaction is treated perturbatively as an expansion over the number of exchanged photons. So far, zeroth-order many-electron wave-function constructed as a Slater determinant (or sum of Slater determinants) with all electrons involved [1,2,3] were used in the performed derivations. The vacuum redefinition in QED, which is extensively used in MBPT to describe the states with many electrons involved, is proposed as a path towards an extension of two-photon-exchange calculations to other ions and atoms. Its benefit is the translation of the one-electron two-loop gauge-invariant subsets into many-electron system .

The two-photon-exchange diagrams for atoms with single valence electron are investigated. Calculation formulas are derived for an arbitrary state within rigorous bound-state QED framework utilizing the redefined vacuum formalism. This approach enables the identification of gauge-invariant subsets at two- and three-electron diagrams and separates between the direct and exchange contributions at two-electron graphs . Thus, the consistency of the obtained results is verified by comparing the results for each identified subset in different gauges. The gauge invariance of found subsets is demonstrated both analytically (for an arbitrary state) as well as numerically for 2s, $2p_{1/2}$, and $2p_{3/2}$ valence electron in Li-like ions [4]. The presented redefined vacuum approach can be further employed for atoms with a more complicated electronic structure, as F-like ions [5].

Moreover, the identification of gauge-invariant contributions within this approach paves the way for calculating the higher-order corrections, which can be splite into gauge-invariant subsets and tackled one after the other.

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Coulomb Corrections to Delbrück Scattering

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Delbrück scattering is the process in which a photon is elastically scattered by the Coulomb field of a nucleus or ion via the production of virtual electron-positron pairs. It is one of the few non-linear quantum electrodynamical processes that can be observed experimentally [1] and, hence, testing the respective theoretical predictions serves as an important test of the Standard model in strong electromagnetic fields. However, despite the strong motivation for the theoretical analysis of Delbrück scattering, most of the previous studies have been limited to some approximation regarding the coupling between the virtual electron positron pair and the nucleus. For example, many authors have used the first-order Born approximation in which all interactions with the Coulomb field beyond the lowest-order are neglected [2]. The accuracy of this approximation wanes for higher nuclear charges which are of particular experimental interest. In this contribution, therefore, we present an efficient approach to calculate amplitudes for Delbrück scattering [3]. Our formalism is based on the exact analytical Dirac-Coulomb Greens function and, hence, accounts for the interaction with nucleus to all orders including the Coulomb corrections.

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A dual-species optical clock to investigate variations of the fine-structure constant and test local position invariance

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Optical clocks realize transition frequencies between atomic energy levels with a relative uncertainty below 10^{-18}. Frequency ratio measurements between optical clocks can reach even lower uncertainties if systematic shifts are common mode for the atomic references like environmental disturbances or result from the same atomic parameter. This precision can be used to search for violations of local position invariance by exploiting the dependence of transition frequencies on fundamental constants like the fine structure constant α. An ion particularly suited to this task is $^{171}Yb^{+}$. It provides two optical clock transitions from the ground state to the first and second excited state, an electric octupole (E3) transition and an electric quadrupole (E2) transition, respectively. Because of the large mass of the ion, both transition frequencies show a large sensitivity on a variation of α and the difference in the electronic structure of the two excited states leads to a dependence of opposite sign. Repeated measurements of the ratio of the two transition frequencies provide the most stringent limits on temporal drifts of α and a potential dependence on the gravitational field [1]. To further enhance the performance of the $^{171}Yb^{+}$ clocks and clearly distinguish clock shifts from variations of α, we employ $^{88}Sr^{+}$ co-trapped in the same apparatus. $^{88}Sr^{+}$ also features an E2 clock transition but its frequency only weakly depends on α. Furthermore, this ion can be used for sympathetic cooling and to investigate systematic frequency shifts of the $^{171}Yb^{+}$ E3 transition on a magnified scale. We present progress towards combined clock operation with both species and a first precise measurement of the ratio of the $^{88}Sr^{+}$ E2 and the $^{171}Yb^{+}$ E3 transition frequencies. Here, we demonstrate an in-situ evaluation of the effective temperature of thermal radiation perturbing the ion and of oscillating magnetic fields using $^{88}Sr^{+}$.

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Relativistic effects of gravity in Earth-based optical cavities

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Leading-edge technologies, like atomic clocks and gravitational wave detectors, can rely on highly stable Fabry-Pérot cavities for frequency stabilization. These devices are capable to stabilize the frequency of a laser to a relative precision of $\delta\nu/\nu=10^{-17}$. Optical cavities, therefore, rank among the world's most precise tools in modern physics. In most of all applications, such a cavity is placed in a laboratory on our planet's surface. As known from the theory of general relativity, the propagation of light in an Earth-based experiment is subject to gravity. This also holds true for light wave propagation in a Fabry-Pérot cavity. We theoretically investigated the influence of gravity on laser-cavity setups [1,2] and found that gravitational light deflection has a potentially measurable impact on the cavity output. Based on our theoretical results, we propose a measurement scheme for the cavity internal light deflection effect, that allows to study the coupling of gravity and light in a well-controlled experimental environment. We emphasize that studies of this kind can provide a new channel to test general relativity and alternative theories of gravity.

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A superconducting radio-frequency quadrupole resonator for metrology experiments with highly charged ions

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Gaining quantum control over motional modes of cold, highly charged ions (HCI) had been a challenge for the last decades and was first accomplished recently utilizing quantum logic spectroscopy (QLS) of the M1 transition in boron-like argon, which was sympathetically cooled by a single beryllium ion [1]. Due to their high sensitivity on beyond the Standard Model observables and the possibility to extend current frequency standards to higher frequencies, HCI are of great interest [2]. Some of their transitions in the XUV obtain extremely long lifetimes and give the ability to reach fractional uncertainties below 10^{-19} in near future. To provide an environment free of noise induced by external alternating electromagnetic fields, we developed a quasi-monolithic, superconducting quadrupole resonator inside the Cryogenic Paul Trap Experiment (CryPTEx-SC) at the Max-Planck-Institute for Nuclear Physics in Heidelberg, Germany reaching a very high Q-factor up to 10^5 at the working frequency of about $34\ \mathrm{MHz}$ [3]. While the Meissner-Ochsenfeld-effect shields the ions from external magnetic field fluctuations, the motional heating of the radial modes is directly suppressed due to the fidelity of the quadrupole fields. Therefore, the cavity provides a promising environment to increase coherence times for QLS experiments, which will lead the way to future measurements of HCI in the Lamb-Dicke regime.

Complementing the trap, we have designed a 50-mm diameter magnifying objective covering a $500\ \mu\mathrm{m}$ field-of-view at a working distance of $57\ \mathrm{mm}$, and optimized for imaging of the trapped Be+ ions at $313\ \mathrm{nm}$. To contain the resonator fields and not compromise the quality factor with normal conducting surfaces, the eight-lens system is directly mounted on top of the superconducting resonator and operates at $4\ \mathrm{K}$. We discuss our design and give insights to current measurements.

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Sympathetic cooling of separately trapped ions coupled via image currents

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Cooling of particles is essential for a variety of experiments with trapped charged particles. While laser cooling techniques have been outstandingly successful in the past, many species of interest lack suitable electronic transitions for direct laser cooling. In this contribution, I will present the recent achievement of sympathetically cooling a single proton with laser-cooled Be+ in a double-Penning-trap system [1]. The two species independently induce image currents in their respective trap electrodes and coupling between them is achieved by connecting one or more electrode of each trap to a common RLC circuit. We demonstrate incoherent cooling of the proton from 17.0 K to 2.6 K. This coupling technique requires only a wire connection and allows a macroscopic separation between the two species, in our case over 9 cm.

Besides reviewing the work in Ref. [1], I will present the current efforts to decrease the proton temperature further. This includes coherent coupling schemes using a detuned RLC circuit, which we have studied in detail with simulations [2]. We find that a dedicated cooling scheme can achieve a proton temperature of 10 mK with a cooling time constant of 10 s. In contrast, established methods such as feedback-enhanced resistive cooling with image-current detectors are limited to about 1K in 100s.

At the time of this abstract, the appartus to realize these findings experimentally is being commissioned, for which I will present the latest status.

Since this sympathetic cooling technique is applicable to any trapped charged particle and allows spatial separation between the target ion and the cooling species, it could enable a variety of precision measurements based on trapped charged particles to be performed at improved sampling rates and with reduced systematic uncertainties.

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Precision spectroscopy of the 2S-6P transition in atomic deuterium

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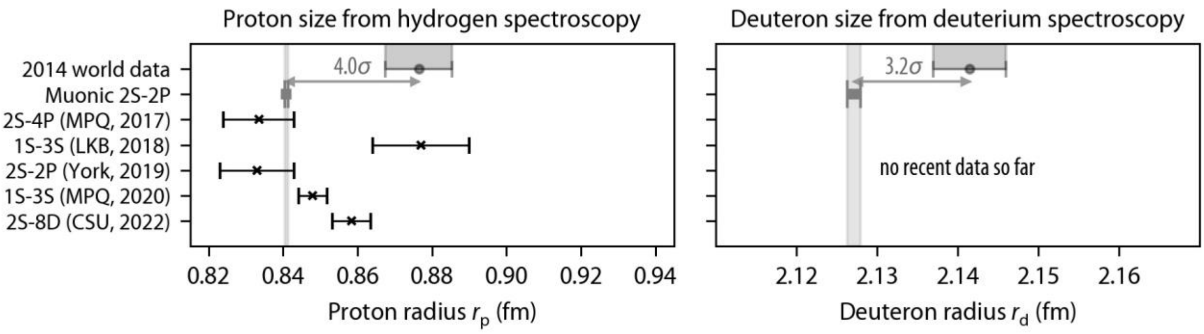
Similar to atomic hydrogen, precision laser spectroscopy of atomic deuterium can be used to determine physical constants and to test Quantum Electrodynamics. A combination of the 1S-2S transition frequency with additional measurements in deuterium allows a determination of the deuteron radius independent of the proton radius [1]. These determinations are however discrepant with results obtained in muonic deuterium [2], similar to the proton radius puzzle in hydrogen. Contrary to hydrogen (e.g. [3]), no recent measurements in deuterium are available:



In contrast to hydrogen, precision spectroscopy of the same transition in deuterium is complicated by the simultaneous excitation of unresolved hyperfine components, possibly leading to quantum interference between unresolved lines [4]. Since these effects depend on laser polarization, we developed an active fiber-based retroreflector with a polarization monitor [5]. Furthermore, we find that in our case the quantum interference is strongly suppressed. We performed a preliminary measurement of the 2S-6P transition in deuterium, which demonstrates the feasibility of determining this transition frequency with a similar precision as for hydrogen.

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X-ray Emission Study Performed for Hydrogen-like Lead Ions at the Electron Cooler of CRYRING@ESR

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The study of x-ray emission associated with Radiative Recombination (RR) at ultra-cold cooling conditions, as it prevails at electron cooler devices at ion storage rings allows for a stringent test of atomic structure and the investigation of subsequent x-ray emission characteristics. In particular, for highly charged ions at high Z it enables us to probe in detail the prevailing cascade decay dynamics and gain more insight into the final state population of the recombination process itself.

We report on an experiment where bare lead ions were decelerated down to 10 MeV/u in the ESR storage ring at GSI, Darmstadt and injected into CRYRING@ESR [1] and, subsequently, the x-ray emission of H-like lead ions associated with the RR process were studied at the electron cooler. For this purpose, at the extension part of cooler section dedicated vacuum chambers were used, equipped with beryllium view ports allowing for x-ray detection under 0° and 180° with respect to the ion beam axis. The x-ray detection was accomplished by using two standard high-purity germanium x-ray detectors. In order to suppress the dominant background, stemming from bremsstrahlung caused by cooler electrons and the natural background, an ion detector was operated downstream to the cooler, enabling to record x-rays in coincidence with down-charged Pb^{81+} ions from electron cooler section.

In this experiment, we observed for the very first time for stored ions the full x-ray emission pattern. Most remarkably, at 0° no line distortion effect due to delayed emission are present in the well resolved spectra, spanning over a wide range of x-ray energies (from about 5 to 100 keV) which enable to identify fine-structure resolved Lyman, Balmer as well as Paschen x-ray lines along with the RR transitions into the K-, L- and M-shell of the ions. To compare with theory, an elaborate theoretical model has been applied taking into account the initial population distribution via RR for all atomic levels up to Rydberg states with principal quantum number n = 165 in combination with cascade calculations based on time-dependent rate equations. Most notably, this comparison sheds light on the contribution of prompt and delayed x-ray emission to the observed x-ray spectra, originating in particular from Yrast transitions into inner shells.

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