Book of Abstracts

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22nd to 26th of May, 2023

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Poster Session Tuesday - 23rd of May, 2023

Two-Photon Exchange in Precision Measurements of Nucleon Electromagnetic Form Factors

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Electromagnetic form factors are fundamental properties of the nucleon that were measured in a variety of electron-scattering experiments involving either polarized or unpolarized particles. The accuracy of existing measurements of specific observables requires sub-per-cent level understanding of the scattering amplitude which, in turn, requires considerations beyond a first Born approximation [1]. Recent positron-scattering experiments tested QED effects dependent on the nucleon structure, while single-spin asymmetries probed the absorptive part of the two-photon scattering amplitude. An ongoing MUSE experiment at PSI aims to address a problem of proton's charge radius in a comparative analysis of scattering of electrons, muons, and their anti-particles on a proton target.

In this presentation, I will give an overview of both theoretical and experimental developments in the studies of hadronic-structure-dependent QED corrections and focus on theoretical issues and approaches to their solutions.

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Measurement of hyperfine structure and the Zemach radius in $^6\mathrm{Li}^+$ using optical Ramsey technique

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High precision spectroscopy of heliumlike ions such as Li^+ provides an important platform in the search for new physics beyond the standard model [1, 2], and a unique measuring tool for nuclear properties [3]. The Zemach radius of the $^6\mathrm{Li}^+$ isotope with spin 1 is a particular case in point where there is a marked disagreement between the value obtained from nuclear structure models [4], and that derived from the atomic hyperfine structure (hfs) coupled with high precision atomic theory [5, 6].

In this presentation, we report the measurement results of hfs in the $2\,^3S_1$ and $2\,^3P_J$ states of $^6\mathrm{Li}^+$, with smallest uncertainty of about 10 kHz. We investigate the $2\,^3S_1$–$2\,^3P_J$ ($J = 0, 1, 2$) transitions in $^6\mathrm{Li}^+$ using the optical Ramsey technique and achieve the most precise values of the hyperfine splittings of the $2\,^3S_1$ and $2\,^3P_J$ states. The present results reduce the uncertainties of previous experiments by a factor of 5 [7] for the $2\,^3S_1$ state and a factor of 50 [8] for the $2\,^3P_J$ states, and are in better agreement with theoretical values. Combining our measured hyperfine intervals of the $2\,^3S_1$ state with the latest quantum electrodynamic (QED) calculations, the improved Zemach radius of the $^6\mathrm{Li}$ nucleus is determined to be 2.44(2) fm, with the uncertainty entirely due to the uncalculated QED effects of order $m\alpha^7$. The result is in sharp disagreement with the value 3.71(16) fm determined from simple models of the nuclear charge and magnetization distribution. We call for a more definitive nuclear physics value of the $^6\mathrm{Li}$ Zemach radius.

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Calculation of isotope shifts and King plot nonlinearities in Ca$^+$

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High-precision spectroscopy is currently in the spotlight of experimental research, particularly as a means of testing physics beyond standard model. One of the methods to detect new interactions is King plot analysis [1]. Recently, a significant King-plot nonlinearity has been discovered in Yb$^+$ transitions [2, 3]. In contrast, King plots in a succession of Ca$^+$ isotopes were found to be linear within experimental uncertainties [4]. However, if the overall measurement uncertainty reaches 1 Hz level in the future—which is realistic—King-plot linearity in Ca$^+$ might no longer hold. Our aim is to lay ground for an interpretation of Ca$^+$ King plot nonlinearity. We calculate energy-level isotope shifts of $4s$, $4p_{1/2}$, $4p_{3/2}$, $3d_{3/2}$ and $3d_{5/2}$ single-electron states of Ca$^+$ for isotopes A =40, 42, 44, 46, 48 using many-body perturbation theory. We include the leading first-order contributions—mass shift and field shift—as well as smaller corrections such as higher-order field shifts, quadratic mass shift, nuclear polarization contribution and the cross term between field and mass shifts. Additionally, we examine King-plot nonlinearities introduced by the higher-order isotope-shift corrections to the combinations of $3d_{3/2} \to 4s$, $3d_{5/2} \to 4s$, and $4p_{1/2} \to 4s$ transitions. Second-order mass shift and nuclear polarization correction are identified as the dominant sources of possible nonlinearity.

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Abstract ID : **67**

Dark Matter Searches at LNF with the PADME detector

Content

The evidence of dark matter so far is based only on gravitational effects observed at cosmological level. To explain these effects, many theoretical models suggest other non-gravitational very-weak interactions between dark matter and ordinary matter. To test this hypothesis, different experiments are trying to directly produce dark matter at particle accelerators.
The Positron Annihilation into Dark Matter Experiment (PADME), ongoing at the Laboratori Nazionali di Frascati of INFN, is looking for signals of hidden particles by studying positron-electron annihilations.
The experiment was built and commissioned at the end of 2018 and collected $\approx\ 5 \times 10^{12}$ positrons on target in two distinct run periods.
The dark photon signal is searched studying the reaction $e^+e^- \ \to \gamma A'$ and evaluating the missing-mass spectrum of single photon final states. This requires a precise calibration of the experimental setup that has been performed evaluating the cross section of the process $e^+e^- \ \to \gamma\gamma(\gamma)$ at $\sqrt{s}$= 20 MeV. The obtained results is the most precise determination of this physics quantity ever done, at it shows a good agreement with NLO-QED predictions.
In 2022 PADME had also a new data taking to study "X17 anomaly", a tricky phenomenon observed by the Atomki collaboration of Debrecem in the de-excitation via internal-pair-creation of some light nuclear systems (i.e. ^8Be, ^4He, ^{12}C). PADME owns the unique opportunity to test the particle hypothesis of such anomaly. Therefore, with a slightly modifying experimental setup, a dedicated data taking was performed. In the talk the details of the ongoing analyses will be presented.

Primary authors: FERRAROTTO, Fabio (INFN - National Institute for Nuclear Physics); Dr GIANOTTI, Paola (INFN Laboratori Nazionali di Frascati (IT))

Presenter: FERRAROTTO, Fabio (INFN - National Institute for Nuclear Physics)

Track Classification: precision measurements in fundamental physics, astrophysics and cosmology

Contribution Type: Oral presentation

Submitted by **Dr GIANOTTI, Paola** on **Friday, 24 March 2023**

Testing the photon and foundations of electromagnetism

Alessandro D. A. M. Spallicci (Université d'Orléans – Centre National de la Recherche Scientifique)

Collaboration
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The Standard-Model Extension (SME) induces a mass to a photon [1,2], the only SM free massless particle. Observations of Fast Radio Bursts [3-5] and solar wind plasma [6,7] allowed estimates and limits listed in the Particle Data Group reviews. SME, classic (de Broglie-Proca and others) massive and non-linear electromagnetism theories (Born-Infeld, Heisenberg-Euler and others) determine a frequency shift of the photon in presence of a background, with which it exchanges energy [8]. This shift, added to expansion red shift, determines new cosmological scenarios, e.g., without recurring to the accelerated expansion to explain Supernovae data [9-11]. The upper limit of this shift would be 7.7×10^{-27} Delta f/f per metre which implies 2.9×10^{-18} in Delta f/f for an interferometer simulating the Earth-Moon distance. Finally, we apply the Heisenberg principle in the energy-time form to cosmological scales and read the Hubble constant as quantum measurement [12,13].

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Matrix elements of the energy-momentum tensor in the hydrogen atom

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This talk will present radiative corrections and their interpretation for the so-called D-term. This is related to the Electron-Ion Collider project in the Brookhaven National Laboratory, USA, where Generalized Parton Distributions (GPD) will be measured. GPD give access to matrix elements of the energy-momentum tensor of a nucleon. The D-term is sometimes roughly interpreted as characterizing pressure distribution. Calculated in simple bound states such as the hydrogen atom it exhibits an interesting new type of a logarithmic correction that resembles the Lamb shift [1, 2] but has a different physical interpretation [3].

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

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R. Pohl[3], **T. W. Hänsch**[1,4], **Th. Udem**[1,4]

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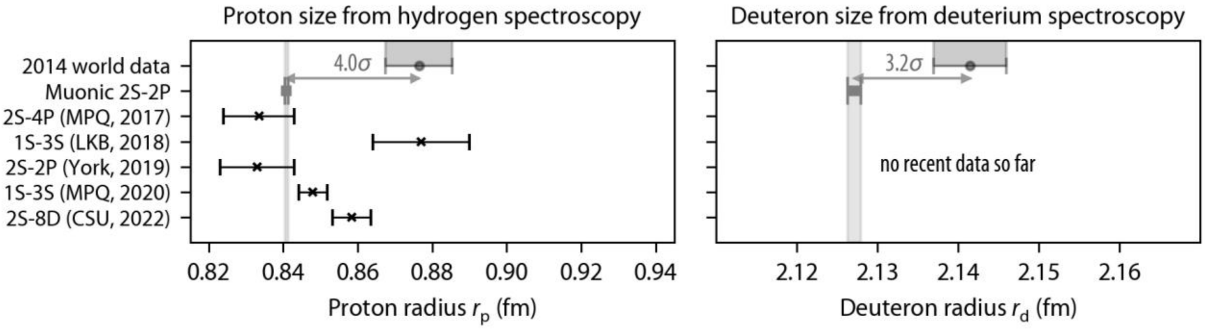
[4] *Ludwig Maximilian University, Munich, Germany*

Both atomic hydrogen and deuterium can be used to determine physical constants and to test bound-state Quantum Electrodynamics (QED). By combining at least two transition frequency measurements in each isotope, the proton and deuteron radii, along with the Rydberg constant, can be determined independently [1]. This is particularly interesting because of the tensions within the recent hydrogen measurements, which leaves room to speculate about possible new physics [2], as well as because no recent deuterium measurements are available such that a discrepancy with muonic deuterium persists [3]:



Using our improved active fiber-based retroreflector to suppress the Doppler shift [4], we recently measured the 2S-6P transition in hydrogen with a relative uncertainty below one part in 10^{12}, allowing one of the most stringent tests of bound-state QED. Here, we report on the status of the ongoing analysis. We also performed a preliminary measurement of the same transition in deuterium. In contrast to hydrogen, the 2S-6P measurement in deuterium is complicated by the simultaneous excitation of unresolved hyperfine components, possibly leading to quantum interference between unresolved lines [5]. Our detailed study of these and other effects in deuterium demonstrates the feasibility of determining the 2S-6P transition frequency with a similar precision as for hydrogen.

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Avogadro and Planck constants, two fundamental pillars of the SI

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In 2018, the General Conference of Weights and Measures reformed the International System of Units [1] by adopting stipulated values of some fundamental physical constants. Today, the kilogram, kelvin, mole, and ampere are related to the Planck (h), Boltzmann (k), and Avogadro (N_A) constants and the elementary charge (e), respectively. The units of time, length, and luminous intensity remain unchanged. They were already defined in terms of constants: the frequency of the radiation emitted in the hyperfine transition of the unperturbed ground-state of the caesium-133, the speed of light, and the luminous efficacy. Yesterday, the kilogram was defined and realised by the international prototype. Today, the kilogram is related to the Planck constant. In this way, it is possible to extend the mass scale above and below 1 kg with accuracies which could not be achieved with the international prototype. The *mise-en-pratique* for the definition of the kilogram [2] recommends two complementary primary experiments for the realisation of the unit of mass. The first experiment, the Kibble electrodynamic balance, measures, through the virtual comparison of electrical and mechanical powers, the ratio between the reference mass and the Planck constant. The second experiment counts the Si 28 atoms, whose mass has been measured in advance, in a macroscopic sphere. In general, each experiment relating a mass to the Planck constant is a primary weighing (at its level of uncertainty). Since 2018, two international key-comparisons of primary methods have been done. The result is that the mass scale has drifted by a few micrograms since the adoption of the new SI.

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[1] 9th edition of the SI brochure, https://www.bipm.org/en/publications/si-brochure
[2] Mise en pratique for the definition of the kilogram in the SI, Appendix 2 of the 9th edition of the SI brochure, https://www.bipm.org/en/publications/mises-en-pratique

Contribution ID: **100**

Type: **Invited Talk**

Testing the quantum nature of gravity in table top experiments

Monday, 22 May 2023 16:40 (40 minutes)

not yet available

Primary author: ASPELMEYER, Markus (University of Vienna)

Presenter: ASPELMEYER, Markus (University of Vienna)

Session Classification: Monday 4

Track Classification: quantum standards

Cavity-Enhanced Precision Spectroscopy of Molecules

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Precise determination of ro-vibrational transition frequencies of molecules is interested in metrology as well as fundamental physics. However, the accuracy is often limited by miscellaneous broadening effects (Doppler, collision, etc) and the weakness of the transitions. The use of high-finesse optical cavities not only enhances the detection sensitivity, but also provides a strong laser field which may saturate weak overtone transitions. Cavity-enhanced spectroscopy techniques combined with frequency combs allow us to determine the center frequencies of molecular Lamb dips with sub-kHz accuracy. Precise two-photon spectroscopy was also implemented with milli-Watt narrow-linewidth lasers. In this talk, I will present our recent progress in precision spectroscopy of the hydrogen molecule and also the demonstration of a “clock” based on infrared molecular transitions. Precise frequencies of the molecular hydrogen may allow a determination of the proton-to-electron mass ratio, and the comparison between the molecular clock and an atomic clock may provide a detection of the variation of fundamental constants or a probe of the mass-dependent new physics.

Fano-like Resonance due to Interference with Distant Transitions

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Precision spectroscopy of narrow transitions of atoms and molecules has been the subject of numerous studies in recent decades and has been widely applied in sensing,metrology, and frequency references for optical clocks [1,2]. Narrow optical resonances also provide excellent probes for determining fundamental physics constants, such as the Rydberg constant [3] and the proton-to-electron mass ratio[4-6]. In these studies, accurate transition centers derived from fitting the measured spectra are demanded, which critically rely on the knowledge of spectral line profiles.

Here, we propose a new mechanism of Fano-like resonance induced by distant discrete levels[7] and experimentally verify it with Doppler-free spectroscopy of vibration-rotational transitions of CO_2 . The observed spectrum has an asymmetric profile and its amplitude increases quadratically with the probe laser power. Our results facilitate a broad range of topics based on narrow transitions.

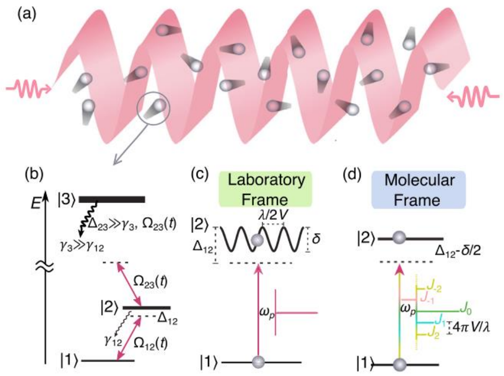

Fig1. Principle of the nonlinear Fano resonance in low-lying states of molecules. (a) The experimental arrangement for the absorption spectrum measurement of moving molecules, probed by a standing wave field with wavelength λ. (b) Energy level diagram. (c),(d) Simplified energy level diagram for a molecule with speed V in the laboratory frame (c) and in the molecular

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Cavity-enhanced double resonance spectroscopy of HD

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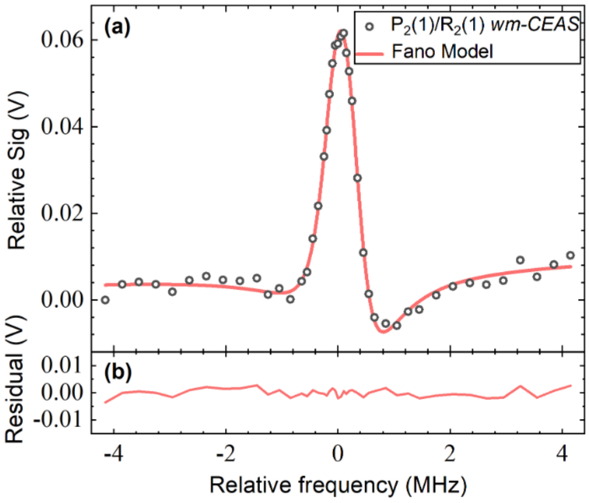
Precision spectroscopy of molecular hydrogen and its isotopes, combined with accurate calculations, allows us to test the fundamental quantum chemistry theory and to determine the fundamental physical constants such as the proton-to-electron mass ratio[1,2]. In general, high overtone transitions may allow for measurements with a better fractional accuracy. However, direct measurement of high overtones, for example, the $v = 4 - 0$ one, turns out to be difficult because the transition moment is extremely small. It is possible to access the $v = 4$ state with two-photon spectroscopy, in which two-step excitation is involved.

Here we present the low-temperature comb-lock Cavity-enhanced system to determine highly-excited rotation-vibration energies of HD with high precision. As a demonstration, the V-type double resonance spectroscopy of HD is measured by pumping the P(1) (2 − 0) line and probing the R(1) line in the same overtone band[3]. In the future, we propose to use this method to determine the rotationless overtone band center (4-0) of HD. The DR method is feasible to determine the pure vibrational frequency $E_{v=4} - E_{v=0}$ ($J = 0$) with an accuracy of a few kHz, which allows for a test of the high-order ab initio calculation.



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Energy levels of the hydrogen molecule from relativistic nonadiabatic calculations

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The theoretically derived energy of a molecular rovibrational level is composed of several additive components: nonrelativistic, relativistic, quantum electrodynamic, etc. For a light molecule, like hydrogen or its isotopologue, this energy can be well described in the framework of the nonrelativistic quantum electrodynamic theory (NRQED) using the following expansion in powers of the fine structure constant

$$E(\alpha) = \sum_{i=2}^{\infty} \alpha^i E^{(i)} . \tag{1}$$

The accuracy of the theoretically predicted energy is limited mainly by its least accurate component. In recent years, we have developed a variational method of solving the Schrödinger equation which treats the hydrogen molecule as a four-particle system without separation of nuclear and electronic motions [1–5]. As a result, the uncertainty of the dominating, nonrelativistic component of the energy, $E^{(2)}$, has reached the level of 10^{-7} – $10^{-8}\,\mathrm{cm}^{-1}$ ($<$ 3 kHz). A typical procedure of decomposing the energy into the clamped nuclei, adiabatic, and nonadiabatic components can hardly enable such an accuracy.

In this communication, we report on extending this nonadiabatic method to the relativistic correction term, $E^{(4)}$. The four-body exponential wave function is applied to evaluate the expectation value of the Breit-Pauli Hamiltonian. The main obstacle encountered in this approach is the need for a whole class of integrals resulting from combining relativistic operators with exponential basis functions. Such integrals

$$\int dV \, \frac{e^{-t\, r_{AB}}\, e^{-u\,(\zeta_1+\zeta_2)}}{r_{AB}^p\, r_{12}^p\, r_{1A}^p\, r_{1B}^p\, r_{2A}^p\, r_{2B}^p}\, R^{n_0}\, r_{12}^{n_1}\, \eta_1^{n_2}\, \eta_2^{n_3}\, \zeta_1^{n_4}\, \zeta_2^{n_5} , \tag{2}$$

where one of the integer powers $p = 2$ and the remaining $p = 1$, have been successfully evaluated, and the preliminary results of the relativistic correction will be reported. The convergence analysis shows that the numerical uncertainty of this correction is of the order of $10^{-7}\,\mathrm{cm}^{-1}$. As in the case of the nonrelativistic component, the relativistic term uncertainty is small enough to enable its elimination from the overall uncertainty budget. An essential feature of the newly developed method is its applicability to an arbitrarily high rotational angular momentum without significant loss in accuracy. With the new relativistic results, augmented by QED corrections, the achieved accuracy is limited limited only by the uncertainty of the quantum electrodynamic effects, $E^{(n)}$, $n \geq 5$.

Several recent measurements [6–12] have indicated a systematic discrepancy between the most accurate theoretical and experimental data. A confrontation of the selected rovibrational transition energies will be made. Possible explanations of this observation will be discussed, setting hints for further theory development.

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Lamb dip of a quadrupole transition in H_2

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The saturated absorption spectrum of the hyperfine-less S(0) quadrupole line in the (2-0) band of H_2 is measured at $\lambda = 1189$ nm, using the NICE-OHMS technique under cryogenic conditions (72 K). It is for the first time that a Lamb-dip of a molecular quadrupole transition is recorded. At high intracavity powers of 0.5-10 kW the line shape corresponds to a complex profile, comparable to previous measurements on HD by our team [1,2] and by the Hefei team [3]. Surprisingly, at low (150-200 W) saturation powers a single narrow Lamb-dip is observed. It is found that the linewidth of this resonance rules out an underlying recoil doublet of 140 kHz, as to be expected under saturation conditions. Systematic measurements on pressure shifts and power shifts were performed and extrapolations to zero-levels fitted. These procedures yield a transition frequency for the S(0) line of (preliminary) 252 016 361 165 (5.0) kHz, which is off by -2.6 (1.6) MHz from molecular quantum electrodynamical calculations [4] therewith providing a challenge to theory.

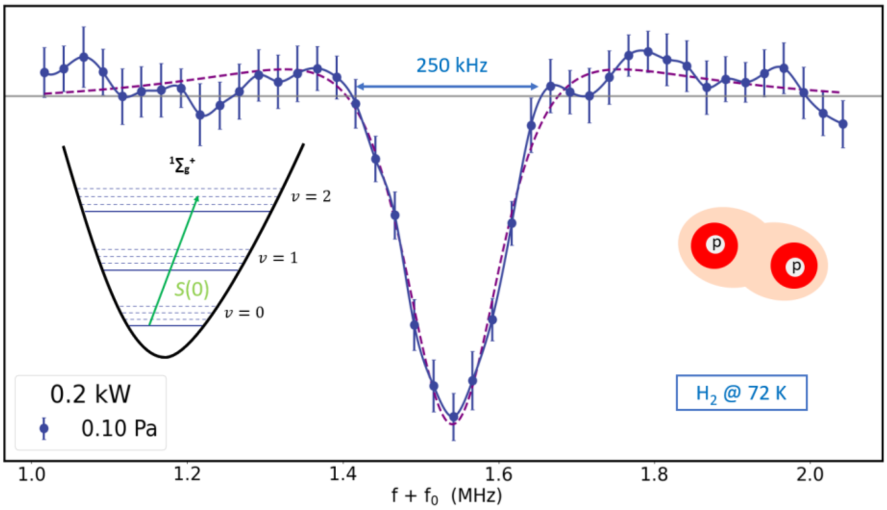

Figure 1: Spectrum of the S(0) quadrupole line of H_2 recorded with NICE-OHMS. The absolute frequency scale, calibrated by a frequency comb laser is given via $f_0 = 252\ 016\ 360$ MHz.

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Sub-Doppler ro-vibrational spectroscopy on HT

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Tests of molecular quantum electrodynamics in the hydrogen benchmark species have predominantly targeted stable isotopes such as H_2, HD, and D_2. Accurate dissociation energy measurements [1] have shown remarkable agreement with theoretical predictions [2,3]. While various cavity-enhanced techniques have been employed to measure vibrational splittings, particularly in HD [4,5], these endeavors have encountered challenges due to dispersive line shapes with multiple interpretations [6,7], restricting the precision of determining molecular vibrational level splittings. However, comparisons of numerous P and R lines have enabled the determination of highly accurate rotational level splittings [7].

Incorporating tritium-containing isotopologues in QED tests of hydrogen species provides new perspectives and deepens our understanding of these systems. Coherent Anti-Stokes Raman spectroscopy (CARS) has recently been utilized to measure vibrational splitting in T_2, HT, and DT [8], albeit with an accuracy limited to a few MHz. We aim to significantly enhance the accuracy by employing our developed NICE-OHMS technology to measure the HT overtone spectrum. We have developed a specialized setup for HT spectroscopy under radiation safety conditions. Loading and handling the HT gas is done by employing an non-evaporable getter (Fig. 1). We anticipate presenting initial results from this novel setup at the upcoming meeting.

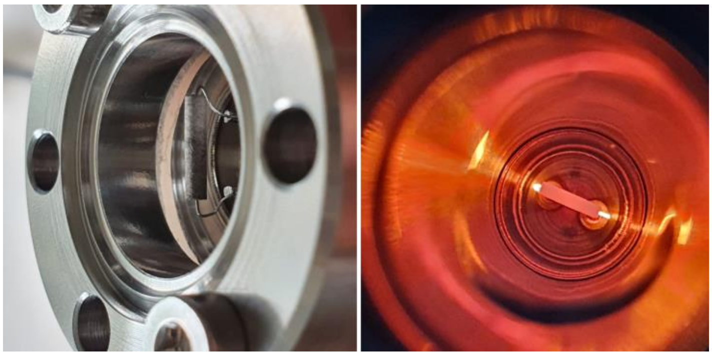

Figure 1. Left-side: Non-evaporable getter for tritium handling and loading. Right-side: Thermal image of the getter during heating and gas loading (900 °C).

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Nonadiabatic QED correction for hydrogen molecule

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The hydrogen molecule lies on the bleeding edge of both experimental and theoretical spectroscopy. Agreement between them at the 1 MHz level and below allows for verification of quantum electrodynamical (QED) and nonadiabatic effects description in bound systems, as well as serves as a cross-check for measurements. On the other hand, a discrepancy can be even more interesting and stimulating for research. For example, despite the constant progress in the theory [1] and the experiment [2], there still exist transitions in HD (e.g. 1–0 $R(0)$) with a noticeable ($\approx 2\sigma$) disagreement. The most likely cause on the theoretical side are the mixed nonadiabatic-QED effects, which have previously been included only for the ground rovibrational state of H_2 [3].

Derivation of formulas for these contributions is quite demanding in the perturbational (NAPT) framework. Instead, we approach the problem by solving the full Schrödinger equation in a “fully nonadiabatic” basis of explicitly correlated Gaussian (ECG) functions, which contain the electronic and the nuclear coordinates on an equal footing. This allows us to include the nuclear-mass-related effects even beyond the leading ones, as well as bypass difficulties present in the perturbational calculations, at the cost of doing it separately for each level considered. We hope our work can restore the consistency between the theory and the experiment for these problematic transitions, as well as help improve the quality of theoretical descripton overall. Furthermore, our precise results can have an added value of being reference points for NAPT calculations in the future.

During the talk, we will describe the methodology used and present the currently available preliminary results.

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International Conference on Precision Physics and Fundamental Physical Constants FFK2023

Abstract ID : **52**

Determination of the Cabibbo-Koyabashi-Maskawa matrix elements |Vcb| and |Vub| at Belle and Belle II

Content

A precise knowledge of the elements $|V_{cb}|$ and $|V_{ub}|$ of the CKM matrix is important to constraint the Standard Model of particle physics and predict the rate of ultra-rare B meson decays such as $B \to \mu\nu$ or $B \to K\nu\bar{\nu}$. In this talk I will review the experimental status of these fundamental parameters with a focus on the latest developments and new results from the Belle and Belle II experiments.

Primary author: SCHWANDA, Christoph (Austrian Academy of Sciences (AT))

Presenter: SCHWANDA, Christoph (Austrian Academy of Sciences (AT))

Track Classification: tests and extensions of the Standard Model of elementary particles

Contribution Type: Oral presentation

Submitted by **SCHWANDA, Christoph** on **Friday, 17 March 2023**

Higgs Boson Searches Beyond the Standard Model from ATLAS and CMS

André Sopczak, on behalf of the ATLAS and CMS Collaborations
Institute of Experimental and Applied Physics,
Czech Technical University in Prague

Abstract

The latest results of Higgs boson searches beyond the Standard Model are reviewed from the ATLAS and CMS experiments. This includes searches for additional neutral, charged and double charged Higgs-like bosons, searches for dark matter produced in association with a Higgs boson and sesarches for new physics in Higgs boson pair production processes. Exotic Higgs boson decays are addressed as well. Interpretations are given in the hMSSM, a special parameterization of the Minimal Supersymmetric extension of the Standard Model in which the mass of the lightest Higgs boson is set to the LHC measured 125 GeV.

Abstract ID : **35**

Superweak extension of the Standard Model

Content

The superweak (SW) force is a minimal, anomaly-free U(1) extension of the standard model (SM), designed to explain the origin of (i) neutrino masses and mixing matrix elements, (ii) dark matter, (iii) cosmic inflation, (iv) stabilization of the electroweak vacuum and (v) leptogenesis. In this talk we discuss how the parameter space of the model is constrained by providing viable scenarios for the first four of this list. The talk will summarize the findings published in the following research articles on the arXiv: 1812.11189, 1911.07082, 2104.11248, 2104.14571, 2105.13360, 2204.07100 and 2301.06621.

Primary author: TROCSANYI, Zoltan Laszlo (ELTE Eotvos Lorand University (HU))

Presenter: TROCSANYI, Zoltan Laszlo (ELTE Eotvos Lorand University (HU))

Contribution Type: Oral presentation

Submitted by **TROCSANYI, Zoltan Laszlo** on **Monday, 13 March 2023**

The n2EDM experiment searching for a neutron electric dipole moment

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on behalf of the nEDM collaboration

[a] *LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble, France*

Searches for permanent electric dipole moments (EDM) of fundamental particles and systems are among the most sensitive probes for CP violation beyond the Standard Model, which is required in order to explain the baryon asymmetry of the Universe. The current limit on the EDM of the neutron is set by our collaboration, |d_n| < 1.8x10^-26 ecm (C.L. 90%) in the nEDM experiment [1]. Presently, a next-generation apparatus - n2EDM - is in the commissioning phase at the ultracold neutron source at the Paul Scherrer Institute (PSI) with the aim of improving the sensitivity by an order of magnitude with provision for further substantial improvements. This presentation will provide an overview of the experiment as well as the commissioning status of the apparatus. Focusing on the most recent progress, we will in particular report on the characterization and optimization of the magnetic environment of the central part of the apparatus, which is a crucial condition to achieve the desired sensitivity.

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Cs in a cryogenic matrix: towards a measurement of the electron electric dipole moment

Sebastian Lahs [a]
on behalf of the EDMMA collaboration
[a]*Université Paris-Saclay, CNRS, Laboratoire Aimé Cotton, Orsay, France*

To explain the open questions in the fundaments of physics, new theories that reach beyond the standard model of particle physics are needed. A great number of these indirectly predict electric dipole moments (EDM) of fundamental particles in ranges that are just within reach for modern atomic and molecular physics experiments. While measurements in atomic and molecular beams, and more recently in ion traps, provided the most successful null measurements of the electron EDM over the past decades, only quite recently did the method of matrix isolation spectroscopy arise. It has the potential advantage of performing spectroscopy on unprecedented numbers of atoms/molecules at once. To perform such a measurement in the future, it is however necessary to first understand how the trapping of atoms inside the cryogenic matrix looks like in detail.

In this contribution, I would like to present what we learned so far through experiments and simulations of cesium trapped in an inert argon matrix and which future steps we are planning to take toward a measurement of the electron EDM and other beyond standard model effects.

High Precision Experiments with Cold and Ultra-Cold Neutrons

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The Neutron and Quantum Physics Group at TU Wien pursues various research approaches in the field of particles and cosmology.

In this talk, I will present a precise determination of the weak axial vector coupling g_A from a measurement of the β-asymmetry in the decay of free neutrons and the relationship to the unitarity of the CKM matrix. New symmetry tests of various kinds are coming within reach with the neutron decay facility PERC at Munich research reactor FRM2 or at ESS, the European Spallation Source. In focus are searches for possible deviations from the Standard Model (SM) of particle physics with cold and ultra-cold neutrons.

Next, we present a novel direct search strategy with neutrons based on a quantum bouncing ball in the gravity potential of the earth. The aim is to test the law of gravitation with a quantum interference technique, providing constraints on dark matter and dark energy.

First Observation of the He^+ 1S-2S Transition in an Atomic Beam

E.L. Gründeman[a], V. Barbé[a], A. Martínez de Velasco[a], M. Collombon[a], K.S.E. Eikema[a]
[a] *LaserLab, Vrije Universiteit Amsterdam, The Netherlands*

Precision spectroscopy of simple, calculable atomic and molecular systems has been an important tool for tests of bound-state quantum electrodynamics, the determination of fundamental constants, and searches for physics beyond the standard model. Singly-ionized helium is a promising alternative system to hydrogen, as high-order QED corrections scale with high powers of the nuclear charge Z [1]. As He^+ is charged, it can be confined in a Paul trap and sympathetically cooled close to the ground state of the trap. To excite the 1S-2S transition, light at extreme ultraviolet (XUV) wavelengths is required, and a method to do precision spectroscopy in this spectral range. We aim to measure this transition with 1 kHz or better accuracy using Ramsey-comb spectroscopy (RCS)[2], combined with high-harmonic generation (HHG)[3].

In RCS, two pulses (near 790 nm) from a frequency comb (FC) pulse train are selectively amplified to the mJ-level, upconverted to the XUV via HHG, and then used to do a Ramsey-type measurement by slightly scanning the repetition frequency of the FC. This is repeated for different pairs of (amplified) pulses of the FC, at different macro-delays that are equal to an integer times the repetition time of the FC. From the relative phase between the Ramsey fringes, the transition frequency is determined, and common-mode phase shifts drop out. For a trapped He^+ ion, this will enable us to cancel the first-order Doppler shift by synchronizing the repetition frequency of the comb to the secular frequency of the helium ion. As a result, Doppler-free excitation will become possible with unequal photons, one at 790 nm, and one at its 25th harmonic (32 nm).

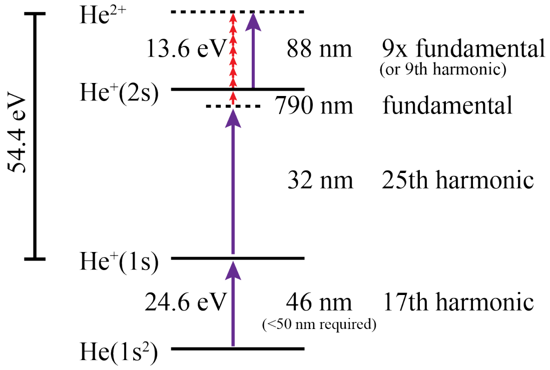

Figure 1: Excitation scheme in the He beam experiment.

We now demonstrate an important step towards this goal with the first laser excitation of the 1S-2S transition in He^+, based on an atomic beam of helium. Within a single 150 fs laser pulse, helium atoms are first ionized to He^+, then excited from the 1S to the 2S state (in He^+) with 32 nm+790 nm, and finally the He^+ ions in the 2S state are ionized again to He^{2+}. By scanning the central wavelength of our frequency comb laser, we can observe the 1S-2S resonance with the He^{2+} signal. We can independently vary the XUV and 790 nm intensity, and show that the observed ac-Stark shifts are consistent with the expected values and are compatible with RCS. This paves the way to high-precision 1S-2S laser spectroscopy of He^+ in an ion trap.

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Towards High-Precision Spectroscopy of the 1S–2S Transition in He^+

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The energy levels of hydrogen-like atoms and ions are accurately described by bound-state quantum electrodynamics (QED). The frequency of the narrow 1s-2s transition of atomic hydrogen has been measured with a relative uncertainty of less than 10^{-14}. In combination with other spectroscopic measurements of hydrogen and hydrogen-like atoms, the Rydberg constant and the proton charge radius can be determined. The comparison of the physical constants obtained from different combinations of measurements serves as a consistency check for the theory [1]. The hydrogen-like He^+ ion is another interesting spectroscopic target for QED tests. Due to their charge, He^+ ions can be held nearly motionless in the field-free environment of a Paul trap, providing ideal conditions for high-precision measurements. Interesting higher-order QED corrections scale with large exponents of the nuclear charge, making this measurement much more sensitive to these corrections compared to the hydrogen case. The measurement of a transition in He^+ will extend the test of QED beyond the long-studied hydrogen. In this talk, we describe our progress towards precision spectroscopy of the 1S-2S two-photon transition in He^+ [2]. The transition can be directly excited by an extreme-ultraviolet frequency comb at 60.8 nm generated by a high-power infrared frequency comb using high-order harmonic generation (HHG). A femtosecond enhancement resonator with non-collinear geometry is used for this purpose. The spectroscopic target is a small number of He^+ ions trapped in a linear Paul trap and sympathetically cooled by co-trapped Be^+ ions. After successful excitation to the 2S state, a significant fraction of the He^+ ions are further ionized to He^{2+} that remain in the Paul trap. Sensitive mass spectrometry using secular excitation will reveal the number of trapped He^{2+} ions and will serve as a single-event sensitive spectroscopy signal.

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High-precision hyperfine structure measurements on hydrogen-like ^{3}He and ^{9}Be

Stefan Dickopf[a], Bastian Sikora[a], Annabelle Kaiser[a], Marius Müller[a], Natalia S.Oreshkina[a], Alexander Rischka[a], Antonia Schneider[a], Stefan Ulmer[b,c], Igor A. Valuev[a], Jochen Walz[d,e], Zoltan Harman[a], Christoph Keitel[a], Andreas Mooser[a] und Klaus Blaum[a]
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[c] *Institute for Experimental Physics, Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany*
[d] *Institute for Physics, Johannes Gutenberg-University Mainz, Germany*
[e] *Helmholtz Institute Mainz, Mainz, Germany*

Spectroscopy of the ground-state hyperfine structure of atoms and ions gives access to the values of the magnetic moments of the bound electron and nucleus and the interaction of the moments - the zero-field hyperfine splitting ΔE_{HFS}.

In our Penning trap setup, such a measurement has recently been carried out on $^{3}\mathrm{He}^{1+}$ to determine the magnetic moment and Zemach radius of its nucleus [1]. To use the magnetic moment for high accuracy magnetic field measurements with ^{3}He-NMR-probes [2] it has to be corrected for by a diamagnetic shielding due to the orbiting electrons. We measure the hyperfine structure of $^{9}\mathrm{Be}^{3+}$ (hydrogen-like) and by comparing it to measurements on $^{9}\mathrm{Be}^{1+}$(lithium-like) we can test the theory of the diamagnetic shielding factor [3, 4]. Additionally, through ΔE_{HFS}, this enables a comparison of the Zemach radius of ^{9}Be extracted from the hydrogen- and lithium-like system [5].

We have measured the magnetic moment of the nucleus with a relative precision of 10^{-9}, making a test of the diamagnetic shielding on the same level possible. The zero-field splitting ΔE_{HFS} extracted from the measurement to a precision of better than one part in 10^{-11} can be used to extract the Zemach radius and compare it the value of the lithium-like system. Recent improvements to our setup further allowed us to determine the bound electron magnetic moment of $^{9}\mathrm{Be}^{3+}$ to a few parts in 10^{-11}, giving an additional high-precision test of QED. The status of the project and future prospects will be presented.

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Theory of the magnetic moments and hyperfine splitting of ^{3}He$^+$

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In an external magnetic field, the ground state of the ^{3}He$^+$ ion is split into into four sublevels due to the combined hyperfine splitting and Zeeman effect. By measuring transition frequencies between these sublevels, it is possible to determine the g-factor of the bound electron, the ground-state hyperfine splitting as well as the shielded magnetic moment of the nucleus [1].
In this work, we present the theoretical calculations of the nuclear shielding constant, the ground-state hyperfine splitting and the bound-electron g-factor [2]. The theoretical uncertainty of the bound-electron g-factor is dominated by the uncertainty of the fine-structure constant α. This would allow an independent determination of α in future, provided that the experimental precision can be improved accordingly [3]. Combining the experimental value for the shielded nuclear magnetic moment and the theoretical value for the nuclear shielding constant, we extracted the magnetic moment of the bare nucleus with unprecedented precision, enabling new applications in magnetometry. Furthermore, we extracted the nuclear Zemach radius from the experimental hyperfine splitting value, in tension with the established literature value [4].

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High precision calculations for helium and helium-like ions

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[b] *Faculty of Mathematics and Physics, Charles University, Ke Karlovu 3, 121 16 Prague 2, Czech Republic*
[c] *Faculty of Physics, University of Warsaw, Pasteura 5, 02-093 Warsaw, Poland*

We will present the current status of QED theory of the helium atom in comparison to precision experimental results. We observe perfect agreement for $2^3S - 2^3P$ transition using the newly obtained muonic helium nuclear charge radius. We also observe excellent agreement for 2^3S hyperfine splitting. However, we observe significant disagreements for 2^3S and 2^3P ionization energies and for the difference of nuclear charge radii obtained from isotope shifts.

Probing Nuclear Size Effects with Precision Spectroscopy of Quantum Degenerate Metastable Helium

Yuri van der Werf, Kees Steinebach, Raphael Jannin, Hendrick L. Bethlem, Kjeld S.E. Eikema
LaserLaB Vrije Universiteit, De Boelelaan 1085, 1081HV Amsterdam, the Netherlands

Precision measurements in simple, calculable systems can be used as sensitive tests for bound-state QED theory, and for a determination of fundamental constants. With this target in mind, we perform precision spectroscopy on the narrow, doubly forbidden $2^3S_1 \rightarrow 2^1S_0$ transition in helium at 1557 nm. To obtain sub-kHz accuracy, we use laser cooling and trapping of atoms in the metastable 2^3S state to prepare quantum degenerate samples. These are trapped in an optical dipole trap at the 320 nm magic wavelength for the transition, where the trap induces no systematic shift on the transition frequency measurement.

Our aim is to determine the squared nuclear charge radius difference between the fermionic ^{3}He, and bosonic ^{4}He isotope, based on a measurement of the isotope shift. For the isotope shift, complicating effects from electron correlations in the QED calculations largely cancel, so that the biggest unknown becomes the finite size of the nuclei. Since the two isotopes exhibit very different quantum-statistical behaviour, the measurements require a profound understanding of fundamental quantummechanical processes. As an example, in the ^{3}He degenerate Fermi gas, we reported a previously unobserved Pauli blockade effect in the excitation dynamics, causing an inherent sub-Doppler narrowing of the spectroscopic linewidths [2].

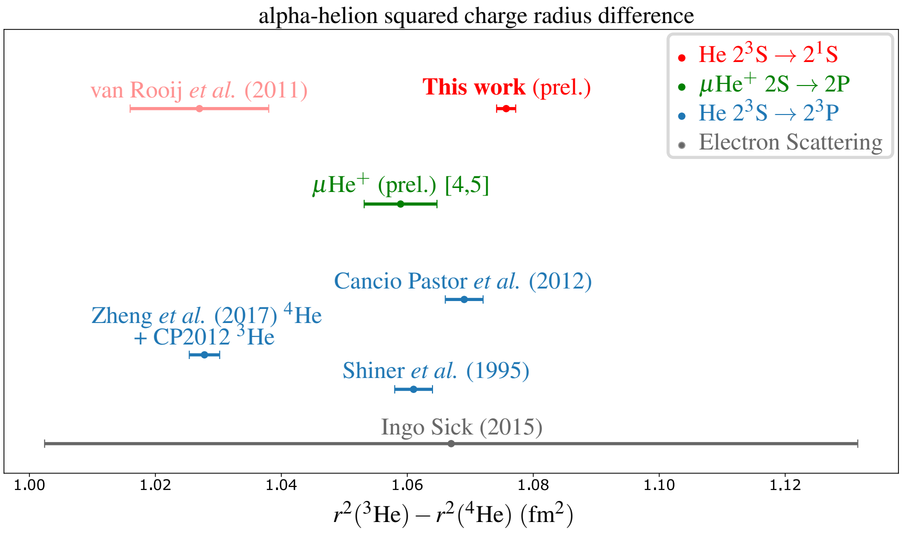

Figure 1: Determinations of the squared charge radius difference δr^2 between the alpha and helion particle. Our newest (preliminary) determination of δr^2 based on the $2^3S_1 \rightarrow 2^1S_0$ transition now gives the most accurate value of δr^2. There are significant discrepancies with other results, among which a (preliminary*) determination from muonic He$^+$ [4,5]. These deviations call for further experimental and theoretical investigation.

In both isotopes, the $2^3S_1 \rightarrow 2^1S_0$ transition has now been measured with a 10^{-12} relative accuracy [1,3], resulting in the most precise determination of the squared nuclear charge radius difference between the alpha and helion particle (see figure 1). Comparing with determinations based on a different transition in helium, as well as measurements of the absolute charge radii in muonic He$^+$ ions, we can check the consistency of the QED theory of helium atoms and test the equivalence between electrons and muons.

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* An updated determination of the helion charge radius from μ^3He^+ is expected soon based on improved theory.

Precision spectroscopy of transitions from the metastable 2 ^{3}S$_1$ state of ^{4}He to high-np Rydberg states

Gloria Clausen[a], Simon Scheidegger[a] , Josef Anton Agner[a] , Hansjürg Schmutz[a], Frédéric Merkt[a]
[a] *Laboratory of Physical Chemistry, ETH Zurich*

The metastable He ((1s)^1(2s)^1) atom in its singlet (^{1}S) or triplet (^{3}S) states is an ideal system to perform tests of ab-initio calculations of two-electron systems that include quantum-electrodynamics and nuclear finite-size effects. The recent determination of the ionization energy of the metastable 2 ^{1}S state of ^{4}He [1] confirmed a discrepancy between the latest theoretical values of the Lamb shifts in low-lying electronic states of triplet helium [2] and the measured 3 ^{3}D ← 2 ^{3}S [3] and 3 ^{3}D ← 2 ^{3}P [4] transition frequencies and could not be resolved in the latest calculations [5, 6]. Currently, we focus on the development of a new experimental method for the determination of the ionization energy of the 2 ^{3}S state of ^{4}He via the measurement of transitions from the 2 ^{3}S$_1$ state to np Rydberg states with unprecedented accuracy. Extrapolation of the np series yields the ionization energy with sub-MHz accuracy.

We present the progress in the development of our experimental setup, which features a Zeeman decelerator and transverse laser cooling and involves (i) the preparation of a cold, supersonic expansion of helium atoms in the 2 ^{3}S state, (ii) the setup and characterization of a laser system for driving the transitions to the np Rydberg states and (iii) the development of a sub-Doppler, background-free detection method. Further, we will provide example spectra of selected np ^{3}P$_J$ ← 2 ^{3}S$_1$ measurements with a prediction of uncertainties for our final measurement campaign.

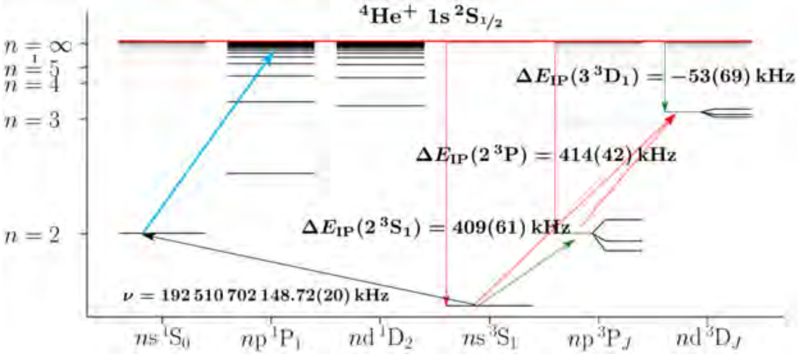

Figure 1: Level diagram of He singlet states (left) and triplet states (right). Comparison of experimentally [1] and theoretically [2] determined ionization energies shown as green and red vertical arrows, where green indicates agreement and red indicates discrepancies.

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Abstract ID : **80**

Status and prospects of the muon magnetic anomaly measurement at FNAL

Content

The Muon g-2 experiment at FNAL measured the muon magnetic anomaly to 0.46 ppm in 2021 and expects to increase the precision on this quantity to 0.23 ppm in 2023 and to 0.14 ppm in 2025, providing a stronger test of the Standard Model prediction, whose uncertainty has been recently estimated at 0.37 ppm. We report on how the measurement is performed, on the improvements with respect to the 2021 published result and on the estimated precision of the incoming measurements.

Primary author: LUSIANI, Alberto (Scuola Normale Superiore and INFN, sezione di Pisa)

Presenter: LUSIANI, Alberto (Scuola Normale Superiore and INFN, sezione di Pisa)

Track Classification: tests and extensions of the Standard Model of elementary particles

Contribution Type: Oral presentation

Comments:

on behalf of the FNAL-E989 collaboration

Submitted by **LUSIANI, Alberto** on **Monday, 27 March 2023**

Contribution ID: **96**

Type: **Invited Talk**

Tension for the anomalous magnetic moment of the muon: 4.2 sigma, indeed?

Wednesday, 24 May 2023 14:30 (45 minutes)

Twenty years ago, in an experiment at Brookhaven National Laboratory, physicists detected what seemed to be a discrepancy between measurements of the muon's magnetic moment and theoretical calculations of what that measurement should be, raising the tantalizing possibility of physical particles or forces as yet undiscovered. The Fermilab team has announced that their precise measurement supports this possibility. The reported significance for new physics is 4.2 sigma just slightly below the discovery level of 5 sigma. However, an extensive new calculation of the muon's magnetic moment using lattice QCD by the BMW-collaboration reduces the gap between theory and experimental measurements. In this talk both the theoretical and experimental aspects are summarized with two possible narratives: a) almost discovery or b) Standard Model re-inforced. Some details of the lattice caluculation are also shown.

Primary author: FODOR, Zoltan

Presenter: FODOR, Zoltan

Session Classification: Wednesday 3

Track Classification: tests and extensions of the Standard Model of elementary particles

Abstract ID : **75**

High-precision calculations of the electron anomalous magnetic moment in quantum electrodynamics

Content

The electron anomalous magnetic moment is the most precise value in microphysics. The agreement between theoretical calculations and experiments is good, but last years it became not so ideal due to an improved experimental precision. The current status of this agreement/disagreement for the electron g-2 will be reviewed as well as for the fine-structure constant.

In 2019 the author has computed a large part of the 5-loop contribution to the electron g-2. It is known that there is a discrepancy between this value and the previously known value. The current status of this discrepancy and independent calculations will be revealed.

Author's method of calculation will be briefly explained, since all computations of this precision level require special methods to make them realizable on existing computers. A progress in further calculations will be demonstrated.

Primary author: VOLKOV, Sergey

Presenter: VOLKOV, Sergey

Contribution Type: Oral presentation

Submitted by **VOLKOV, Sergey** on **Monday, 27 March 2023**

Precision Measurement of Muonium Hyperfine Structure at J-PARC

S. Nishimura[a], S. Fukumura[b], Y. Goto[b], R. Iwai[a] S. Kanda[a], S. Kawamura[b], N. Kawamura[a],
M. Kitaguchi[c], T. Okudaira[b], H. M. Shimizu[b], K. Sasaki[a], K. Shimomura[a], P. Strasser[a], H. Tada[b],
H. A. Torii[d], T. Yamanaka[e], T. Yamazaki[a]
on behalf of the MuSEUM collaboration

[a] *High Energy Accelerator Research Organization (KEK)*
[b] *School of Science, Nagoya University*
[c] *KMI, Nagoya University*
[d] *School of Science, The University of Tokyo*
[e] *School of Science, Kyushu University*

The muonium atom is a bound state of a positive muon and an electron, and is one of the hydrogenlike atoms which consists purely of leptons. By measuring the muonium hyperfine structure, the muon mass and the magnetic moment ratio of the proton to the muon can be determined. These values are used to determine the experimental value of muon $g-2$, for which a discrepancy of 4.2σ between the Standard Model prediction and experimental values has been reported [1], and the importance of these measurements is increasing. We plan to measure the hyperfine structure of muonium with ten times higher precision than the previous experiment [2] by using high-intensity muon beam at J-PARC.

First, we developed a zero-field experiment and observed the resonance curve at the J-PARC MLF D-Line [3]. Experimental setup is shown in Fig. 1. We also established Rabi-oscillation spectroscopy, which reduces systematic uncertainty due to microwave power by directly determining resonance frequency from Rabi oscillations without microwave frequency sweep [4].

The high-field experiment will be performed with the same setup as the zero-field experiment except for the magnetic field and microwave cavity. The pure water NMR probe for high-precision magnetic field measurements has achieved an accuracy of 15 ppb with a single channel, and is being developed for multi-channel measurements over a wide area. The prototype module is shown in Fig. 2. A cylindrical microwave cavity has been completed, and a rectangular cavity is being designed and developed to allow greater freedom in resonance frequency selection. We will report on the status of the above developments.

Figure 1: Setup of the zero-field experiment.

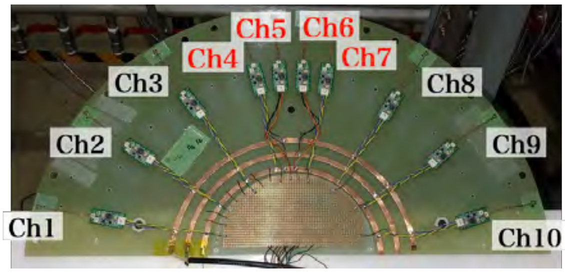

Figure 2: Prototype of multi-channel magnetic probes.

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Recoil and Radiative-Recoil Corrections in Muonium

Gregory S. Adkins[a], Jonathan Gomprecht[a], Yanxi Li[a], and Evan Shinn[a]
[a] *Franklin & Marshall College, Lancaster, Pennsylvania*

Muonium, the $e^-\mu^+$ bound system, is presently the subject of intense experimental activity. The MUSEUM collaboration at J-PARC is mounting an experiment to measure the muonium ground state hyperfine splitting with an uncertainty goal of $5\,\mathrm{Hz}$ $(1.2\,\mathrm{ppb})$ [1]. The MuMASS collaboration at PSI is working on new measurements of the 1S-2S interval and the $n = 2$ Lamb shift. The 1S-2S experiment has a final uncertainty goal of $10\,\mathrm{kHz}$ $(4\,\mathrm{ppt})$ [2, 3]. For the Lamb shift, a new measurement has already reduced the uncertainty by an order of magnitude compared to previous measurements [4] with prospects for significant additional improvement. The leading uncertainties in the QED calculations for these intervals are due to uncalculated recoil and radiative-recoil corrections [3, 5, 6]. It is important to reduce these theoretical uncertainties in order to make the best use of improved experimental results.

In this talk I will report on new results for the recoil and radiative-recoil corrections to muonium energy levels at orders $(Z\alpha)^6$ and $\alpha(Z\alpha)^5$, respectively [7]. These results are exact in the particle masses, eliminating the need for an expansion in the small mass ratio m_e/m_μ. The calculations of the required "hard" integrals (the ones involving relativistic momenta) were done using the integration-by-parts identities in terms of a small set of master integrals, which were evaluated using the method of differential equations [8]. Calculations involving the "soft" (non-relativistic) scale were performed using NRQED. Progress on using the same methods for the calculation of recoil and radiative-recoil contributions at orders $(Z\alpha)^7$, $\alpha(Z\alpha)^6$, and $\alpha^2(Z\alpha)^5$ will be discussed.

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LEMING: Towards the measurement of the gravitational acceleration of exotic muonium atoms

A. Antognini[1,2], M. Bartkowiak[2], P. Crivelli[1], D. Goeldi[1], K. Kirch[1,2], A. Knecht[2], J. Nuber[2], A. Papa[2], R. Scheuermann[2], A. Soter[1], D. Taqqu[1], R. Waddy[1], P. Wegmann[1], J. Zhang[1]

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[2] *Paul Scherrer Institute, 5232 Villigen-PSI, Switzerland*

A direct consequence of the CPT symmetry incorporated in the Standard Model (SM) is the equivalence of various measurable properties of matter and antimatter. However, with the lack of an unified theory between the SM and General Relativity (GR), the equivalence of the gravitational interaction of matter and antimatter cannot be taken for granted. The expected equivalence originates from the weak equivalence principle (WEP) which, among other measurables, implies the universality of free fall for all particles. However, this principle has so far only been rigorously tested with systems composed of first-generation matter particles.

The newly approved LEMING experiment at the Paul Scherrer institute aims to measure the free fall of muonium (Mu $= \mu^+ + e^-$), an exotic atom consisting purely of leptons: an anti-muon and an electron. Measuring the free fall of Mu atoms would be the first test of the WEP using elementary antimatter of the second generation and, additionally, using a system without large contributions to the mass from the strong interaction.

A direct free fall measurement is inherently challenging due to the short lifetime of Mu ($\tau \sim$ 2.2 μs). The experiment will utilize a three-grating atom interferometer, which requires a high-intensity, low-emittance Mu beam. This novel Mu source is being developed based on stopping accelerator muons in a layer of superfluid helium and converting them to a high quality in-vacuo Mu beam.

In this contribution the LEMING experiment is introduced. New measurements on the first observation of Mu emitted from superfluid helium and an initial characterization of the novel Mu source are presented. Implications of the newly developed Mu beam on the prospective gravity experiment will be discussed and the way towards a free fall experiment that would be the first direct measurement of gravitation interactions of (anti-)leptons will be described.

Contribution ID: **90** Type: **Oral presentation**

Electroweak nuclear radii constrain isospin-breaking corrections to V_{ud}

Wednesday, 24 May 2023 17:15 (15 minutes)

The most precise determination of the top-left corner element of the CKM quark mixing matrix V_{ud} is obtained from accurate measurements of superallowed nuclear β decays. Among the theoretical ingredients in this determination, the isospin symmetry-breaking (ISB) correction δ_{C} plays a crucial role in aligning the Ft-values across all superallowed transitions. This alignment allows for a joint analysis of many transitions in terms of V_{ud}, while remaining misalignments are used to set stringent limits on BSM scalar currents. Until recently, δ_{C} could not be directly constrained by observables remaining a purely theoretical input, and the respective uncertainty was hard to estimate reliably. In a series of recent works, we construct combinations of the nuclear charge and weak radii which are connected to δ_{C}. These nuclear radii can be obtained experimentally from a combination of muonic atom spectroscopy, isotope shift measurements, and parity violation in electron scattering, and the corresponding experimental uncertainties can be used for a robust, data-driven and model-independent uncertainty on δ_{C}, empowering tests of CKM unitarity and constraints on BSM with nuclear β decays.

Primary author: GORSHTEYN, Misha (Mainz University)

Presenter: GORSHTEYN, Misha (Mainz University)

Session Classification: Wednesday 4

Track Classification: tests and extensions of the Standard Model of elementary particles

Abstract ID : **14**

Precision spectroscopy of molecular hydrogen ions: recent advances

Content

We present our recent experimental advances on laser spectroscopy of cold, trapped molecular hydrogen ions. The contribution to the determination of fundamental constants and tests of physical laws is discussed.

Primary author: SCHILLER, Stephan

Co-authors: ALIGHANBARI, Soroosh; KORTUNOV, Ivan; SCHENKEL, Magnus R.; VOGT, Victor; WELLERS, Christian

Presenter: SCHILLER, Stephan

Track Classification: fundamental physical constants

Contribution Type: Oral presentation

Submitted by **Prof. SCHILLER, Stephan** on **Tuesday, 28 February 2023**

State preparation for rovibrational transition frequency measurement of HD^+

Sheng-Guo He[a], Yong Zhang[a, b], Qian-Yu Zhang[a, b], Wen-Li Bai[a, b], Zhi-Yuan Ao[a, b], Wen-Cui Peng[a], Xin Tong[a,c]

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[c] Wuhan Institute of Quantum Technology, Wuhan 430206, China

The rovibrational transition frequency of HD^+ molecular ions can be used to determine the fundamental physical constants (such as mp/me), test the quantum electrodynamics (QED) of three-body systems and search for new physics beyond the Standard Model [1-2]. Internal state preparation of the HD^+ ions plays a vital role for improving signal-to-noise ratio in the rovibrational spectroscopic measurement. Here, we report a method for producing ultracold HD^+ molecular ions populated in a rotational ground state in an ion trap [3]. The state-selected HD^+ ions are generated via [2+1'] resonance-enhanced threshold photoionization (RETPI) and subsequently sympathetic cooling by the laser-cooled Be^+ ions. The effect of electric field of the ion trap on the RETPI process of neutral HD molecules and the blackbody radiation (BBR) on the population evolution of rotational states of the generated polar HD^+ ions have been studied. This method of generating ultracold state-selected HD^+ ions is beneficial for the studies in the precision rovibrational spectroscopy, state-controlled cold chemical reaction, and quantum logic spectroscopy.

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[2] I. V. Kortunov, S. Alighanbari, M. G. Hansen, G. S. Giri, V. I. Korobov and S. Schiller, Nat. Phys. 17, (2021), 569.
[3] Y. Zhang, Q. Y. Zhang, W. L. Bai, Z. Y. Ao, W. C. Peng, S. G. He, X. Tong, Phys. Rev. A (accepted).

Hydrogen molecular ions, fundamental constants, and new physics

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[b] Université d'Evry-Val d'Essonne, Université Paris-Saclay, Boulevard François Mitterrand, F-91000 Evry, France

[c] LaserLaB, Department of Physics and Astronomy, Vrije Universiteit Amsterdam, De Boelelaan 1081, 1081 HV Amsterdam, The Netherlands.

In recent years, the accuracy of rotational and vibrational spectroscopy of HD^+ was improved by nearly three orders of magnitude by use of techniques for Doppler-free excitation [1, 2, 3]. Meanwhile, the precision of theoretical transition frequencies was improved to below the level of 10 parts per trillion (ppt), so that it is now mainly limited by the uncertainty of the 2018 CODATA value of m_p/m_e [4].

We present a global analysis of existing data [5], using the theoretical hyperfine structure to extract the values of spin-averaged transition frequencies through a global linear least-squares adjustment. Using the obtained frequencies, we then assess the potential contribution of HD^+ spectroscopy to the determination of fundamental constants. Our analysis shows that the HD^+ data may significantly improve the values of m_p/m_e and of the electron relative atomic mass, in particular if combined with recent high-precision measurements performed in Penning traps.

High-precision spectroscopic data, including HD^+, can be used to constrain hypothetical interactions beyond the standard model, which is usually done by comparing experimental results with predictions from the standard model that use CODATA recommended values of fundamental constants. However, it should be realized that the determination of fundamental constants itself would be affected by the new physics being tested. In a second part, we show how this issue can be solved by simultaneously determining both standard-model and new-physics parameters in a consistent way from a global fit [6]. At present, the data show tensions partly related to the proton charge radius, which can be alleviated by including contributions from a light scalar with flavor non-universal couplings.

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An Optical Atomic Clock Based on a Highly Charged Ion

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Physikalisch-Technische Bundesanstalt, Braunschweig, Germany
Institut für Quantenoptik, Leibniz Universität Hannover, Germany.

Optical atomic clocks are the most precise and accurate measurement devices ever constructed, reaching fractional systematic uncertainties below one part in 10^{18} [1]. Their exceptional performance opens up a wide range of applications in fundamental science and technology. The extreme properties of highly charged ions (HCI) make them highly sensitive probes for tests of fundamental physical theories [2, 3]. Furthermore, these properties make them significantly less sensitive to some of the leading systematic perturbations that affect state-of-the-art optical clocks, making them exciting candidates for next-generation clocks [4, 2]. The technical challenges that hindered the development of such clocks have now all been overcome, starting with their extraction from a hot plasma and sympathetic cooling in a linear Paul trap [5], readout of their internal state via quantum logic spectroscopy [6], and finally the preparation of the HCI in the ground state of motion of the trap [7], which allows levels of measurement accuracy to be reached that were previously limited to singly-charged and neutral atoms. Here, we present the first operation of an atomic clock based on an HCI (Ar^{13+} in our case) and a full evaluation of systematic frequency shifts [8]. The achieved uncertainty is almost eight orders of magnitude lower than any previous frequency measurements using HCI. Measurements of some key atomic parameters confirm the theoretical predictions of the favorable properties of HCIs for use in clocks. The comparison to the $^{171}Yb^{+}$ E3 optical clock [9] places the frequency of this transition among the most accurately measured of all time. Furthermore, by comparing the isotope shift between $^{36}Ar^{13+}$ and $^{40}Ar^{13+}$ to improved atomic structure calculations, we were able for the first time to resolve the largely unexplored QED nuclear recoil effects. Finally, prospects for 5th force tests based on isotope shift spectroscopy of Ca^{+}/Ca^{14+} isotopes and the high-sensitivity search for a variation of the fine-structure constant using HCI will be presented. This demonstrates the suitability of HCI as references for high-accuracy optical clocks and to probe for physics beyond the standard model.

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Ultrastable clock transitions in highly charged ions

Chunhai Lyu, Christoph H. Keitel, Zoltán Harman
Max Planck Institute for Nuclear Physics, 69117 Heidelberg, Germany

Highly charged ions (HCIs) are insensitive to external perturbations and attractive for developing ultrastable clocks. In this contribution [1], we present a set of HCI clock candidates with quality factors and polarizabilities many orders of magnitude larger and smaller, respectively, than those in state-of-the-art clocks. Their transition energies could scale up to the XUV and soft-x-ray region, thus enable the development of clocks based on shorter wavelengths. Furthermore, as the metastable clock states have energies higher than their corresponding ground states, HCIs in such states bear heavier masses that could be detected via mass spectroscopies [2, 3]. We also show that these HCI clock states can be coherently excited via currently available lasers [4]. High-precision laser spectroscopy of these clock transitions will significantly enrich the detection of fine-structure constant variations, the search for new physics, and the test of nuclear theories.

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Penning trap PENTATRAP for fundamental physics

Pavel Filianin, Kathrin Kromer, Menno Door,
Jost Herkenhoff, Christoph Schweiger, Sergey Eliseev, Klaus Blaum

Max Planck Institute for Nuclear Physics, 69117 Heidelberg, Germany

The Penning-trap mass spectrometer Pentatrap [1] located at the Max Planck Institute for Nuclear Physics in Heidelberg is performing mass-ratio measurements with a relative uncertainty in the 10^{-11} regime. One of the unique features of the Pentatrap experiment is the external ion source producing a wide range of charge states from gaseous or solid-state samples down to only 10^{15} atoms. the detection systems with single-ion sensitivity and the simultaneous measurements of two out of three eigenfrequencies in two adjacent traps.

Due to its versatility and high accuracy, Pentatrap can contribute to a variety of topics of fundamental physics. Among them are a test of bound-state QED in strong fields, a search for atomic long-lived metastable states in highly charged ions [2], and a search of dark matter by means of isotope shift spectroscopy. The setup overview and the latest results at Pentatrap will be presented.

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Measurement of the mass difference between tritium and helium-3

Edmund G. Myers and Moisés Medina-Restrepo

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The KATRIN tritium beta-decay neutrino mass experiment has reduced the limit on effective electron neutrino mass to 0.8 eV/c^2 (90% C.L), with an eventual aim of 0.2 eV/c^2 [1]. Using the novel method of cyclotron radiation emission spectroscopy, which inherently provides absolute electron energy calibration, the Project-8 collaboration aims to reach an eventual sensitivity of 0.04 eV/c^2 [2]. Comparing the value for the endpoint of the electron spectrum with the Q-value independently determined from the mass difference between tritium and helium-3 provides an important test of systematics in these experiments.

Here, improving on our previous measurement [3], we present results of a new precision Penning trap measurement of the mass difference between tritium and helium-3, obtained by measuring the cyclotron frequency ratios $HD^+/{}^3He^+$, HD^+/T^+ and $T^+/{}^3He^+$, each with an uncertainty of 10 parts-per-trillion or less. Our method uses pairs of ions simultaneously trapped in a Penning trap, alternated between large and small cyclotron orbits.

Support by the NSF under 1912095 is gratefully acknowledged.

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Towards an Atomic Mass Measurement of the ^{3}He Nucleus with Parts-per-trillion Precision

Olesia Bezrodnova[a], Sangeetha Sasidharan[a,b], Sascha Rau[a], Wolfgang Quint[b], Sven Sturm[a], Klaus Blaum[a]
[a] *Max Planck Institute for Nuclear Physics, Heidelberg, Germany*
[b] *GSI Helmholtzzentrum, Darmstadt, Germany*

The most precise mass measurements of light nuclei today are performed using Penning traps. Together, these measurements provide a network of essential parameters for fundamental physics. For example, the mass difference of T and ^{3}He is used as a consistency check for the model of systematics in the KATRIN experiment, which studies the endpoint of the tritium β-decay spectrum to set a limit on the $\bar{\nu}_e$ mass [1].

Recently performed high-precision mass measurements of the lightest nuclei, including ^{3}He, have revealed considerable inconsistencies between tabulated values reported by different world-leading experiments. This discrepancy is known as the “light ion mass puzzle”. In order to provide an independent cross-check, the multi-Penning-trap mass spectrometer LIONTRAP has obtained the masses of the proton [3], the deuteron and the HD^{+} molecular ion [4]. These measurements are in excellent agreement with the results of the Florida State University [5] [6], as well as HD^{+} spectroscopy. However, there is a disagreement with the values reported by the University of Washington group [7] [8].

Present activities of the experiment are directed at the atomic mass measurement of the ^{3}He nucleus with a relative uncertainty lower than 10 parts-per-trillion. This contribution presents the status of the ongoing measurement campaign.

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High Precision Measurements of Single Ions in the ALPHATRAP Penning Trap Setup

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The ALPHATRAP experiment [1] is a double Penning trap setup at the Max Planck Institute for Nuclear Physics in Heidelberg, Germany. The cryogenic trap setup allows for high precision spectroscopic measurements on single ions while utilizing the continuous Stern-Gerlach effect for state detection [2]. It is connected to a room temperature beamline with access to several different ion sources and thus a wide range of charge states are available for measurements. A cryogenic valve results in a residual pressure of below 10^{-16} mbar in the trap section leading to trapping times of several months.

In this contribution, I will give an overview of our setup and recent measurement campaigns. With our recent determination of the g factor of the bound electron of hydrogen-like tin, we have probed QED in the extreme electric field of the nucleus of 10^{17} V/m. The direct electron g-factor difference of 2 coupled neon ions (^{20}Ne^{9+} and ^{20}Ne^{9+}) measured to 0.56 ppt has, for the first time, resolved the nuclear QED recoil effect [3]. I will focus on the spectroscopy of single molecular hydrogen ions, in particular the hyperfine spectroscopy of HD$^+$ probing spin-spin interaction theory and the currents steps towards rovibrational laser spectroscopy en route to high-precision measurements on single H_2^+ ions for future matter-antimattter comparisons [4].

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QED theory of the g factor of Li-like ions

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Measurements of g-factors of light few-electron ions are combined with advanced *ab initio* theoretical calculations to provide one of the most stringent tests of the bound-state QED theory and the most accurate determination of the electron mass [1, 2, 3]. For light hydrogen-like ions such as C^{5+} and O^{7+}, the current theoretical predictions are capable of matching the 10^{-11} relative precision level achievable in modern experiments. For lithium-like ions, however, the theoretical precision is on the level of 10^{-9} which is an order of magnitude less accurate than the experimental results. Moreover, there was some tension reported in the literature between the theoretical values [4, 5, 6, 7] and experimental results for lithium-like ions.

We here discuss the present status and recent advances in the QED theory of g-factor of light lithium-like ions. *Ab initio* calculations are reported for the electron-structure, self-energy screening, and vacuum-polarization screening effects, without any expansion in the nuclear binding strength parameter $Z\alpha$. Calculations are carried out for different screening potentials, thus varying the starting zeroth-order approximation of the perturbation theory. Comparison of the results obtained with different starting potentials allowed us to access the theoretical uncertainty due to omitted higher-order electron-correlation effects. A subset of higher-order effects for the Coulomb starting potential was calculated and found to yield a surprisingly large numerical contribution. The resulting theoretical values of the g factor of Li-like silicon and calcium are found to be in good agreement with the experimental results.

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Abstract ID : **77**

Tests of physics beyond the standard model with the g factor of few-electron ions

Content

emphasized textIn this contribution, we discuss the theory of the bound-electron g factor. This quantity can be measured nowadays to high precision in Penning-trap setups. The collaboration of theory and experiment enables impactful and detailed tests of quantum electrodynamics in a strong background electric field, and a competitive determination of fundamental constants [1] and nuclear properties [2]. Very recently, we have shown that such studies also allow to test certain extensions of the standard model of particle physics [3]: in study addressing the isotope shift of the g factor of H-like Ne ions, a competitive bound was set on the strength of a hypothetical fifth force by combining the experimental value of the isotope shift with the precision theory of nuclear recoil within QED.

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Presenter: Dr HARMAN, Zoltan (Max Planck Institute for Nuclear Physics)

Track Classification: tests and extensions of the Standard Model of elementary particles

Contribution Type: Oral presentation

Submitted by **Dr HARMAN, Zoltan** on **Monday, 27 March 2023**

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Contribution ID: **103**

Type: **Oral presentation**

Three-Loop Corrections to Lamb Shift in Muonium and Positronium

Thursday, 25 May 2023 17:10 (25 minutes)

Hard spin-independent three-loop radiative corrections to energy levels in muonium and positronium are calculated.
These corrections could be relevant for the new generation of precise 1S-2S and 2S-2P measurements in muonium and
positronium.

Primary author: Prof. EIDES, Michael (University of Kentucky)

Presenter: Prof. EIDES, Michael (University of Kentucky)

Session Classification: Thursday 4

Track Classification: quantum electrodynamics of bound systems

Towards a bound-state relativistic QED approach

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Atomic and molecular few-particle bound states are of interest in both experimental and theoretical precision spectroscopy. In combination with theoretical computations, the experiments are proposed to test our fundamental understanding of ordinary matter in the low-energy range and to probe physics beyond the Standard Model. Relativistic and QED effects are most often treated within the non-relativistic quantum electrodynamics framework, which yields excellent agreement with experimentally measured transitions for low-Z systems (e.g., [1]). Nevertheless the large number of effective interaction terms makes evaluating higher-order corrections increasingly complicated both analytically and numerically. In this contribution, the development of an alternative approach based on the relativistic Bethe–Salpeter wave equation is presented for the simplest two-fermion case. The introduction of the equal-time wave function and separating a non-retarded interaction kernel gives rise to the no-pair Dirac–Coulomb(–Breit) equation, which is solved variationally to high precision using an explicitly correlated Gaussian basis set, treating both relativistic and correlation 'effects' on an equal footing [2, 3, 4, 5, 6]. The method is applied to several two-electron atomic and molecular systems with clamped nuclei, and further extended to pure two-body systems without the Born–Oppenheimer approximation such as positronium, muonium, hydrogen atom, and muonic hydrogen [7]. The numerical results show excellent agreement with the corresponding relativistic perturbative energy contributions. Challenges and advances towards the inclusion of higher-order pair, retardation, and radiative contributions are discussed [8].

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Nuclear structure effects in the Lamb shift of μH and μD

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This presentation concentrates on the two-photon-exchange corrections to the Lamb shift in muonic hydrogen (μH) and muonic deuterium (μD). These effects are the subleading $O(\alpha^5)$ and higher effects of the nuclear structure, and their detailed knowledge is necessary, for instance, for a precise extraction of the nuclear radii from the Lamb shift in muonic atoms [1].

In an ideal case, the bulk of these effects can be extracted from the data on the inclusive electron scattering off the respective nucleus, using the dispersion relations [2]. Specifically, the two-photon-exchange contributions are connected to the spin-independent nuclear structure functions that encode the unpolarised inclusive electron scattering cross section [2]. However, there is a part, the subtraction contribution, that arises due to a subtraction in the dispersion relation and thus cannot directly be inferred from experimental data. This term is particularly important in μH, and one way to quantify it is using the covariant baryon chiral effective field theory (BχEFT).

In heavier muonic atoms, starting from μD, the purely nuclear subtraction contribution is convergent [3], while the contributions of individual nucleons are suppressed. However, the quantity and quality of the data on the nuclear structure functions are not satisfactory, which makes ab initio calculations of the two-photon-exchange contributions the preferable method [4].

In this presentation, I will discuss the results obtained for the two-photon-exchange effects in μH based on BχEFT, concentrating on the subtraction contribution [5]. Furthermore, I will discuss the respective results for μD, calculated in the pionless effective field theory [6, 7], with emphasis on the single-nucleon contribution (which, in turn, is based on the BχEFT results for μH). In particular, I will stress that the subtraction contribution dominates the theoretical uncertainty in μH, and that the single-nucleon two-photon exchange, despite being suppressed compared to the purely nuclear effects, is significant in μD. The latter effect, as well as its uncertainty, is even more important in heavier muonic atoms. This provides a strong motivation for further studies aimed at constraining the electromagnetic properties of the nucleons, such as the electric and magnetic polarisabilities.

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Present status of spectroscopy of the hyperfine structure and repolarization of muonic helium atoms at J-PARC

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The muonic helium atom ${}^4\mathrm{He}\mu^- e^-$ is an atom in which one of the two electrons of the ${}^4\mathrm{He}$ atom is replaced by a negative muon. Since the orbital radius of the negative muon is about 400 times smaller than the Bohr radius, we can treat $({}^4\mathrm{He}\mu^-)^+$ as a pseudo-nucleus that has a magnetic moment similar to that of a negative muon, and consider a muonic helium atom as a hydrogen-like atom. The ground state hyperfine structure (HFS) of muonic helium atom is caused by the interaction between the magnetic moments of the electron and the negative muon. The HFS of muonic helium atom is similar to muonium, which is a purely leptonic system consisting of positive muon and electron, and it can be measured using the same apparatus and technique as for muonium ground state HFS [1-2].The Experimental setup is shown in Fig. 1.

The measurement of the HFS of muonic helium atom has the potential to improve the precision of the mass of the negative muon by a factor of 50 or more. The mass of the negative muon is very important because it enables us to test the CPT theorem by comparison with positive muon mass. In addition, since muonic helium atom is a three-body system, precise HFS measurements of muonic helium atom will be a powerful probe to test and improve the theory of quantum three-body systems [3].

In previous experiments [4-5], measurement precisions are limited by mainly statistical uncertainty. The reason for the large statistical uncertainty is not only the beam intensity but also the loss of muon spin polarization ($\sim$100% $\rightarrow \sim$ 6%) due to Auger transitions and Stark mixing associated with the formation of muonic helium atom. This depolarization of muons can be recovered by using the Spin Exchange Optical Pumping (SEOP) technique [6]. Our setup of muonic helium repolarization is shown is Fig. 2. We aim to determine the ground state HFS of muonic helium atom with one hundred times higher precision than previous experiments by using the high-intensity negative muon beam of J-PARC and SEOP technique.

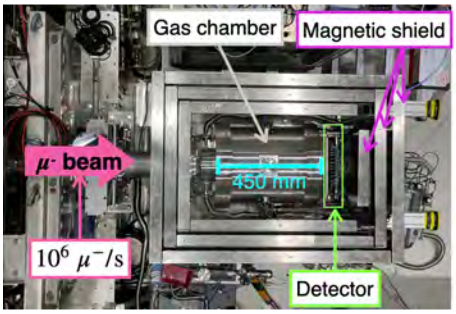

Figure 1: Setup of the HFS measurement.

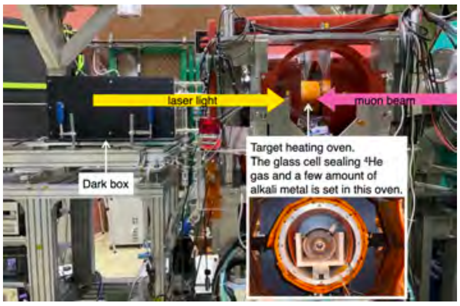

Figure 2: Setup of muonic helium repolarization using SEOP.

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An update on the muonic fine-structure puzzle

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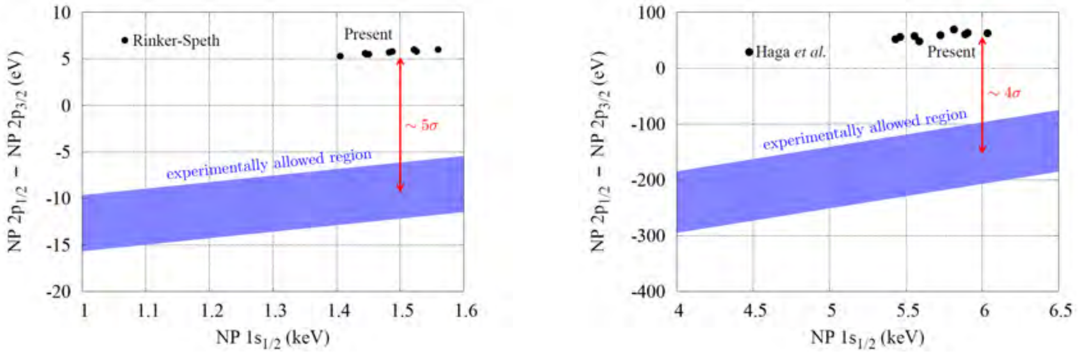
According to the principle of lepton universality, the only fundamental difference between the electron and the muon is their mass, namely $m_\mu \approx 207 m_e$. This simple fact has profound consequences for the so-called muonic atoms formed via capturing a muon by the nucleus of an ordinary atom. The muonic Bohr radius is 207 times smaller than the electronic one, which makes the muon an excellent probe to study essential nuclear properties. In practice, this is done by fitting theoretical muonic transition energies to measured ones while treating the nuclear property of interest as a free parameter. However, in a series of heavy muonic atoms such a procedure resulted in very poor fits (see, e.g., [1]), where the source of the discrepancies was narrowed down to the fine-structure splitting between the $2p_{1/2}$ and $2p_{3/2}$ energy levels. Remarkably, this muonic fine-structure puzzle has persisted for decades and stills remains unresolved to this day.

From the theoretical side, the most challenging and uncertain contribution to calculate is the nuclear polarization effect, which describes the dynamic interplay between atomic and internal nuclear degrees of freedom. For a long time, nuclear polarization has been naturally considered to be the main suspect responsible for the discrepancies. However, our recent study [2] provided strong evidence against this prevalent hypothesis (see Fig. 1). Furthermore, taking a closer look at the QED part of the calculations and improving the evaluation of the self-energy correction also did not alleviate the problem [3].



(a) (b)

Figure 1: Theoretical values of the nuclear-polarization corrections for μ-^{90}Zr (a) and μ-^{208}Pb (b) in relation to the experimentally allowed regions for $\left(|\Delta E^{\mathrm{NP}}_{2p_{1/2}}| - |\Delta E^{\mathrm{NP}}_{2p_{3/2}}|\right)$ and $|\Delta E^{\mathrm{NP}}_{1s_{1/2}}|$ [2].

An overview of the current status of the puzzle will be presented, and other potential solutions will be discussed, including some more exotic ideas such as contributions from new hypothetical interactions beyond the Standard Model.

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Towards a precision measurement of charge radii of light nuclei

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Precise knowledge of nuclear properties such as charge and Zemach radii, as well as nuclear polarizabilites; are key for a better understanding of nuclear forces, the determination of fundamental physical constants, tests of bound-state QED and searches for New Physics. In this talk I will present QUARTET (QUAntum inteRacTions with Exotic aToms), a new experiment which aims to improve the charge radii of light nuclei from ^{6}Li to ^{22}Ne by up to an order of magnitude [1]. To accomplish this we will employ metallic magnetic calorimeters for x-ray spectroscopy of low-lying states in muonic atoms. These detectors offer for the first time the combined capability of a high quantum efficiency, high resolving power, and broadband capacity [2]. I will discuss the importance of these radii for benchmarking *ab initio* nuclear theory, as well as their interface with the next generation of precision measurements in light Helium-like ions [3, 4, 5].

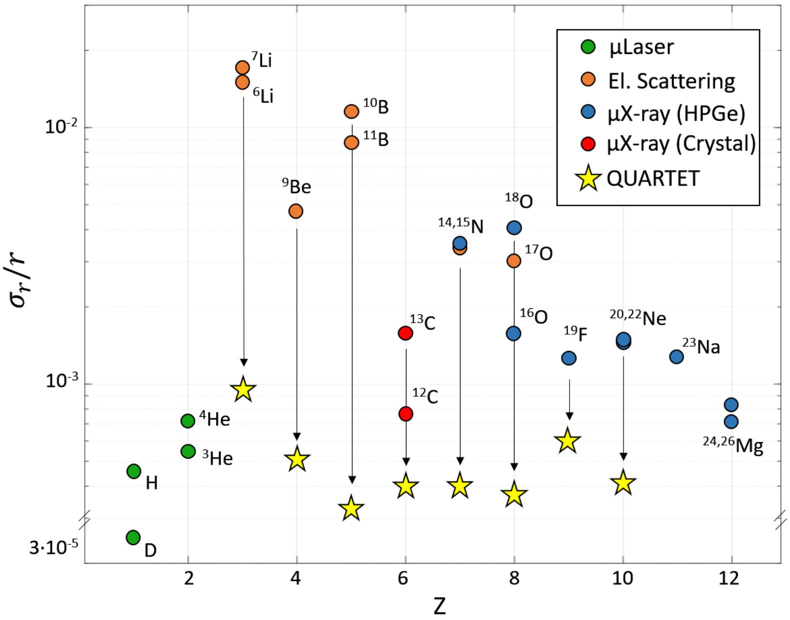

Figure 1: Current status and precision goals for charge radii of light stable nuclei.

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Testing fundamental physics with trapped antihydrogen

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Antimatter and gravity are subjects of two of the biggest mysteries in physics. The universe exhibits an excess of matter over antimatter, and unifying gravity and quantum mechanics remains an open challenge. Antihydrogen, the simplest purely antimatter atomic system, is a promising candidate for investigating these fundamental questions [1]. CPT symmetry predicts that the spectra of hydrogen and antihydrogen should be identical, making antihydrogen a tool for precision tests of this symmetry due to the well-understood hydrogen spectrum. Additionally, antihydrogen's electric neutrality makes it an ideal probe of the gravitational interaction between matter and antimatter.

The ALPHA experiment at CERN has made significant progress on both fronts. Major results have recently been published on spectroscopy [2, 3] and cooling [4] of antihydrogen. Additionally, the recently constructed and commissioned ALPHA-g apparatus has enabled a test of Einstein's weak equivalence principle with an antihydrogen gravitational free-fall experiment. This talk will discuss the most recent results from the ALPHA collaboration on spectroscopy and gravity measurements with antihydrogen as well as future prospects for precision measurements.

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Studies of Exotic Physics with Antiprotons and Protons

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The Standard Model of particle physics is incredibly successful and glaringly incomplete. Among the questions left open is the striking imbalance of matter and antimatter in our universe, which inspires experiments to compare the fundamental properties of matter/antimatter conjugates with high precision. The BASE collaboration at the antiproton decelerator of CERN is performing such high-precision comparisons with protons and antiprotons. Using advanced cryogenic Penning traps, we have recently performed the most precise measurement of the proton-to-antiproton charge-to-mass ratio with a fractional uncertainty of 16 parts in a trillion [1]. In another measurement, we have invented a novel spectroscopy method, that allowed for the first direct measurement of the antiproton magnetic moment with a fractional precision of 1.5 parts in a billion [2]. Together with our last measurement of the proton magnetic moment [3] this improves the precision of previous magnetic moment based tests of the fundamental CPT invariance by more than a factor of 3000. A time series analysis of the sampled magnetic moment resonance furthermore enabled us to set first direct constraints on the interaction of antiprotons with axion-like particles (ALPs) [4], and most recently, we have used our ultra-sensitive single particle detection systems to derive constraints on the conversion of ALPs into photons [5]. In parallel we are working on the implementation of new measurement technology to sympathetically cool antiprotons [6] and to apply quantum logic inspired spectroscopy techniques [7]. I will review the recent results produced by BASE, with particular focus on the recent 16 p.p.t. comparison of the antiproton-to-proton charge-to-mass ratio and recent developments towards an improved measurement of the antiproton magnetic moment.

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Laser spectroscopy of antiprotonic helium embedded in liquid and superfluid helium

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Metastable antiprotonic helium is a three-body exotic atom composed of a helium nucleus, an electron in the 1S state, and an antiproton occupying a highly excited state with principal and orbital angular momentum quantum numbers of $n \approx l$-1≈38 [1-5]. The atom retains a microsecond-scale average lifetime against antiproton annihilation in the helium nucleus.

We carried out laser spectroscopy of these atoms embedded in liquid and superfluid helium targets at the Antiproton Decelerator of CERN [1]. The visible-wavelength spectral lines of the atom were found to retain a sub-gigahertz linewidth in superfluid helium. This is much narrower than the optical spectral lines of many other normal-matter atoms placed in liquid helium. An abrupt reduction in the linewidth of the antiprotonic transition was observed when the liquid surrounding the atom transitioned into the superfluid phase. The hyperfine structure arising from the spin–spin interaction between the electron and antiproton was resolved with a relative spectral resolution of two parts in 10^6. No quantitative theoretical explanation for this effect has been found so far [1,3].

Metastable pionic helium [6-11] is composed of a helium nucleus, a negative pion, and an electron. We used the 590 MeV ring cyclotron facility of Paul Scherrer Institute to carry out laser spectroscopy of this atom and observed a pionic transition $(n,l)=(17,16)\rightarrow(17,15)$ having a spectral linewidth of 100 GHz [9]. The above experimental results of antiprotonic helium imply that the resolution of the pionic helium measurements may also be vastly increased. This may assist us in determining the charged pion mass with a higher precision than before [6,9,11].

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Abstract ID : **91**

A positron trap for observing molecules containing positronium

Content

A positron trap is a powerful and adaptable tool for performing experiments with positrons and positronium. These devices use a strong magnetic field, a stepped potential well and Nitrogen and CF_4 buffer gas. Positrons are initially trapped via the electronic excitation of N_2, CF_4 is added for efficient cooling via vibrational and rotational excitations. This type of positron trap can typically produce ~105 e+/s in bunches with a diameter of 1-2 mm and an energy spread of approximately 50 meV [e.g. 1,2].

We aim to use the positron pulses from such a trap to observe molecules containing positronium, such as PsH [3] and PsO [4] via collisions in gases such as methane and carbon dioxide. By using a high mass resolution ion spectrometer to detect fragments from dissociation, precise measurement of their binding energy will be performed.

This poster will describe the positron beam, trap, and ion spectrometer from the newly constructed positron beamline in Vienna.

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Presenter: WEISER, Alina (Austrian Academy of Sciences (AT))

Track Classification: spectroscopy of exotic atoms

Contribution Type: Poster presentation

Submitted by **WEISER, Alina** on **Wednesday, 3 May 2023**

Accurate determination of the Born-Oppenheimer potential and relativistic correction for light molecules

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The helium hydride ion (HeH^+) and the helium molecular ion (He_2^+) are some of the first particles that emerged as a result of the Big Bang. They were both formed and destroyed on similar pathways during the processes of the early Universe[1,2], which makes them especially interesting from the point of view of astronomical research.

Their similarity in the atomic structure to a hydrogen molecule opens up the way to conduct highly accurate spectroscopic analyses[3-6] and also to obtain theoretical approximations of rovibrational levels of a similar accuracy. The co-validation of theoretical and spectroscopic results is then necessary. It consists of comparing transitions visible on the spectrum with those theoretically predicted.

To obtain such precise results, we utilize explicitly correlated Gaussian functions and use the NRQED (nonrelativistic quantum electrodynamics) approach[7] as well as the nonadiabatic perturbation theory (NAPT)[8]. Thanks to this, we are able to determine the Born-Oppenheimer (BO) potential and a multitude of corrections (relativistic, nonrelativistic, QED effects) with the highest possible accuracy. In our work, we present the results of deriving the BO potential as well as the relativistic correction for both HeH^+ and He_2^+.

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Development for the precise microwave spectroscopy of muonium with a high magnetic field

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M. Kitaguchi[c], S. Nishimura[b], T. Okudaira[a], K. Sasaki[a], H. M. Shimizu[a], K. Shimomura[b],
P. Strasser[b], H. A. Torii[d], T. Yamanaka[e], T. Yamazaki[b]
on behalf of the MuSEUM collaboration

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[b] *High Energy Accelerator Research Organization (KEK)*
[c] *KMI, Nagoya University*
[d] *School of Science, The University of Tokyo*
[e] *School of Science, Kyushu University*

The MuSEUM collaboretion is planned at J-PARC to measure the hyperfine structure of muonium (Mu HFS) at high magnetic field (1.7 T). The goal is to presicely test the Standard Model and determine the fondamental constants.

The MuSEUM collaboration aims to measure the Mu HFS transition energy with an accuracy of 1.2 ppb and determine the magnetic moment ratio of the muon proton with an accuracy of 12 ppb, resulting in an order of magnitude improvement compared to the previous experiment [1]. In 2023, we perform the first measurement with a high magnetic field at high intensity pulsed muon beamline (H-line). In this measurement, the transition frequency depends on the magnetic field because the measurement is based on the Zeeman splitting produced by the magnetic field (see Fig.1). Whereas, this measurment requires a very uniform magnetic field (0.2 ppm, peak-to-peak) in a large spectroscopy volume (ϕ 20 cm and L 30 cm). To overcome this challenge, we are developing a magnetic field distribution measurement system with a resolution smaller than 10 ppb using a CW (Continuous Wave)-NMR probe [2], and passive shiumming technique. We are developing a magnetic field measurement system (see Fig.2) in which multiple CW-NMR probes are arranged in a semicircle circumference to enable measurement in a short time. In this poster, various key technologies of contorolling the magnetic field are presented.

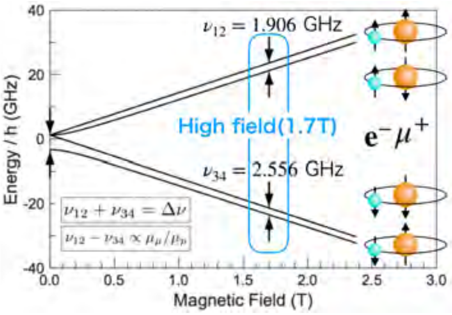

Figure 1: The energy levels of muonium under a magnetic field.

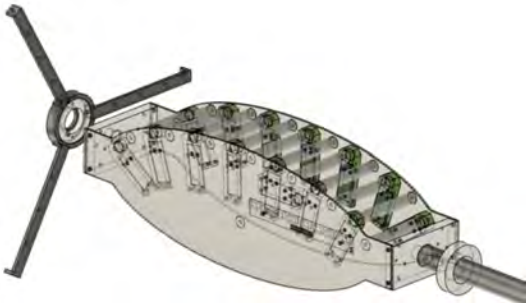

Figure 2: Magnetic field measurement system

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Abstract ID : **105**

Future BSM studies using UPCs with ALICE at the LHC

Content

The search for physics beyond the Standard Model (BSM) is one of the main goals of the LHC. Compared to standard proton-proton collision studies, heavy-ion collisions provide unique and complementary means to search for new phenomena. In particular, ultra-peripheral collisions (UPCs) of heavy ions offer a natural environment for the studies of photon-mediated processes, such as light-by-light scattering, axion-like particle searches and τ $g-2$ measurements.

A precise experimental determination of the tauon anomalous electromagnetic moment a_τ is of great interest, since it increases the sensitivity to BSM physics by a factor of $m_\tau/m_\mu \sim 280$ compared to measurements with muons. However, while the anomalous electromagnetic moments of the electron and muon were measured with high precision, results on tauons are still rather poor. The current best limits are 15 years old and were obtained by the DELPHI collaboration by a measurement of the $e^+e^- \to e^+e^-\tau\tau$ cross section. Here we will discuss a method for measuring a_τ in heavy-ion UPCs and provide prospects for such a measurement with ALICE in the LHC Run 3.

In addition we will provide an outlook on measurements with ALICE 3, the proposed next-generation LHC experiment for LHC Run~5 and beyond. At that time, the upgraded LHC accelerator will deliver beams of high luminosity, which together with a novel detector design will enable detailed studies of light-by-light scattering and to search for axion-like particles in a poorly explored range of diphoton invariant masses from 50 MeV/c^2 to 5 GeV/c^2.

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Track Classification: tests and extensions of the Standard Model of elementary particles

Contribution Type: Poster presentation

Submitted by **LAVICKA, Roman** on **Thursday, 11 May 2023**

Abstract ID : **71**

Ground state preparation for HD+ rovibration transition measurement

Content

Generation of ground state HD+ based on the [2+1'] resonance-enhanced threshold photoionization (RETPI) is provided for rovibrational transition frequency measurement. Using state-selected [1+1'] resonance-enhanced multiphoton dissociation, the yield of rovibrational ground state HD+ is evaluated. The state preparation of HD+ lay an important basis of the proceed measurement which detects the (v=0,j=0)⟶(v=6,j=1) rovibrational transition frequency.

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Presenter: ZHANG, QianYu (APM of CAS)

Contribution Type: Poster presentation

Submitted by **ZHANG, QianYu** on **Monday, 27 March 2023**

Pre-Born–Oppenheimer Dirac–Coulomb–Breit computations for two-fermion systems

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Positronium, muonium, hydrogen atom, and muonic-hydrogen are the simplest, yet some of the most extensively studied bound-state systems. High-precision spectroscopy experiments in combination with theoretical computations are proposed to test our fundamental understanding of ordinary matter in the low-energy range and to probe physics beyond the Standard Model. So far almost exquisitely relativistic and QED effects are treated within the non-relativistic quantum electrodynamics framework, which yields excellent agreement with experimentally measured transitions [1]. An alternative approach based on the relativistic Bethe–Salpeter wave equation was developed for the simplest two-fermion case in an external Coulomb field [2, 3, 4, 5, 6, 7]. The introduction of the equal-time wave function and separating a non-retarded interaction kernel gives rise to the no-pair Dirac–Coulomb(–Breit) equation, which is solved variationally to high precision. The advantage of the approach is that both correlation and special relativity are accounted for already in zeroth order. In this contribution, the extension of the Dirac–Coulomb(–Breit) framework is presented to pure two-body systems: positronium, muonium, hydrogen atom, and muonic-hydrogen as the first applications without the introduction of the Born–Oppenheimer approximation [8]. The numerical results show excellent agreement with the corresponding analytic relativistic perturbative energy contributions.

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

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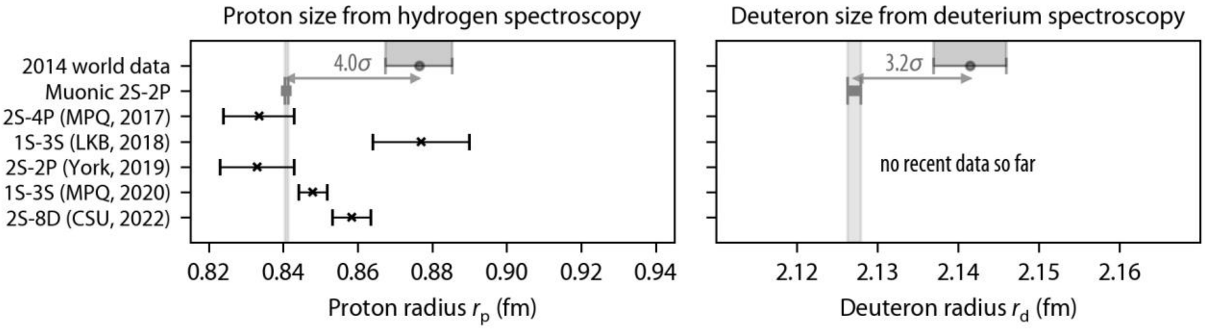
Both atomic hydrogen and deuterium can be used to determine physical constants and to test bound-state Quantum Electrodynamics (QED). By combining at least two transition frequency measurements in each isotope, the proton and deuteron radii, along with the Rydberg constant, can be determined independently [1]. This is particularly interesting because of the tensions within the recent hydrogen measurements, which leaves room to speculate about possible new physics [2], as well as because no recent deuterium measurements are available such that a discrepancy with muonic deuterium persists [3]:



Using our improved active fiber-based retroreflector to suppress the Doppler shift [4], we recently measured the 2S-6P transition in hydrogen with a relative uncertainty below one part in 10^{12}, allowing one of the most stringent tests of bound-state QED. Here, we report on the status of the ongoing analysis. We also performed a preliminary measurement of the same transition in deuterium. In contrast to hydrogen, the 2S-6P measurement in deuterium is complicated by the simultaneous excitation of unresolved hyperfine components, possibly leading to quantum interference between unresolved lines [5]. Our detailed study of these and other effects in deuterium demonstrates the feasibility of determining the 2S-6P transition frequency with a similar precision as for hydrogen.

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Ramsey-Comb Spectroscopy of the $EF^1\Sigma_g^+ - X^1\Sigma_g^+(0,0)$ Q_0 and Q_1 Transitions in Molecular Hydrogen and Deuterium

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As the simplest neutral molecule, molecular hydrogen (H_2) is a good testing ground for molecular quantum theory. Its dissociation energy D_0 has become a benchmark value to test *ab initio* quantum molecular calculations. An experimental value for D_0 can be obtained by relating the ionization energy of H_2, to the ionization energy of atomic hydrogen and the dissociation energy of the H_2 ion. By combining our measurements of the X to EF Q_0 and Q_1 transitions with the determination of the energy difference between the EF state and the continuum carried out at the ETH Zurich [1], we can provide an experimental value for the ionization energy of H_2, and therefore of D_0. In order to measure the Q_0 transition in H_2, we perform 2-photon Ramsey-comb Spectroscopy (RCS) [2] in the VUV at 202 nm. RCS uses two amplified and up-converted pulses out of the infinite pulse train of a frequency comb laser to perform a Ramsey-like excitation. Recent improvements to the experimental setup enabled the determination of the X to EF transition frequency in H_2 and D_2 with 30 and 19 kHz accuracy, respectively [4]. We will report on these measurements and discuss their implications regarding an improved determination of the dissociation energy of H_2 and D_2, and a comparison with theory.

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Report on Cryogenic Micro-Calorimeter Detectors in High-Precision X-Ray Spectroscopy Experiments at GSI/FAIR

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In recent years, cryogenic micro-calorimeter based detectors have proven to become an indispensable tool for high-precision X-ray spectroscopy experiments involving highly charged heavy ions. Due to their unique working principles of converting the incident particle's energy into a proportional rise in temperature in the sensor, they combine several advantages over conventional energy resolving photon detectors. For example, metallic magnetic calorimeters (MMC) – like the maXs-series detectors developed in cooperation with the KIP in Heidelberg – use the temperature dependant change of the sensor's magnetization in a magnetic field in combination with a SQUID-based read-out to convert the absorbed energy into a measurable signal. This yields an intrinsic energy resolution of up to $E/\Delta E \approx 6000$ [1], comparable to crystal spectrometers. At the same time MMCs cover a broad spectral range of several orders of magnitude, comparable to semiconductor based detector systems. Additionally, they posses an excellent linearity with deviations understood from first principles (see for example [2]) as well as a rise time down to $\tau_0 \approx 100\,\mathrm{ns}$ [3], making them particularly well-suited for high precision experiments in fundamental physics.

However, achieving this outstanding performance requires the shift from a traditional analog to a fully digital signal processing scheme. The high sensitivity of the detectors leads to comparably strong susceptibility to fluctuations of operation parameters like external magnetic fields or the substrate temperature. In order to mitigate these effects, a detailed understanding of the detector is essential. Therefore, during the last years, several measurements using multiple MMC detectors have been performed at different experiment facilities of the GSI Helmholtz-Centre for Heavy Ion Research in Darmstadt, Germany (see for example [4, 5, 6]). A comprehensive software framework for MMC signal analysis was developed and benchmarked using the insights gained, preparing MMCs for the deployment as spectrometer detectors for future high precision measurement campaigns. We will report on key results of these experiments and discuss the feasibility of utilizing micro-calorimeter based detectors in fundamental physics research.

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Rovibrational and Hyperfine Structure of the Molecular Hydrogen Ion from Spectroscopy of Rydberg-Stark Manifolds

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H_2^+ is the simplest molecular three-body system, and is therefore of interest from a fundamental point of view. Specifically, precision measurements of rovibrational energies in this system can provide access to fundamental constants such as the proton-to-electron mass ratio or the proton charge radius, by comparison with theoretical results [1]. Because homonuclear isotopologues of molecular hydrogen have no permanent electric dipole, pure rotational and vibrational spectra cannot be measured. Instead, transitions to Rydberg series converging on different rovibrational states of the ion core can be driven in a multiphoton excitation scheme starting from the molecular ground state [2]. Extrapolation of Rydberg series yields the ionic level energies. In this work, we use a combination of high-precision laser spectroscopy and calculations of Rydberg-Stark manifolds including electron and nuclear spins to determine rovibrational and hyperfine intervals in H_2^+ and D_2^+ at sub-MHz accuracy.

Experimentally, precise measurements of Rydberg states with a rovibrationally excited core are challenging because of line-broadening effects caused by autoionization. By applying electric fields, states of different values of ℓ are mixed, which provides access to the non-penetrating states of high-ℓ character and therefore increases the lifetimes. Additionally, the high-ℓ states have vanishingly small quantum defects and form a nearly degenerate Stark manifold. Extrapolation to zero field yields the zero-quantum-defect positions [3], from which the ionization energy can be determined. By applying the zero-quantum-defect-method to states with the ion core in different rovibrationally excited states, energy differences between these ion core states are determined.

For rigorous comparison with the measurements, we present calculations of Stark manifolds including interactions involving electron and nuclear spins. In particular, because previous studies have shown that the calculated manifold positions are sensitive to the zero-field positions of high-ℓ states [3], we show how these positions can be accurately calculated with a simple polarization model [4] to which spin-orbit, spin-rotation and, if necessary, hyperfine interactions are added.

As first applications of the above-mentioned method, we focus on the determination of the fundamental vibrational interval in H_2^+ ($X^+\ {}^2\Sigma_g^+$), the spin-rotation interval in H_2^+ ($X^+\ {}^2\Sigma_g^+$) and the hyperfine splitting in the $X^+\ {}^2\Sigma_g^+$ ($v^+ = 0, N^+ = 0$) ground state of D_2^+.

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Search for the electric dipole moment of the electron using BaF molecules

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T.B. Meijknecht[1,2], M.C. Mooij[2,3], R.G.E. Timmermans[1,2], A. Touwen[1,2],
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The search for the permanent electric dipole moment of the electron (eEDM) is intimately connected to CP-violation. While the Standard Model (SM) predicts the latter to occur, it is insufficient to account for the large matter-antimatter asymmetry observed in the Universe. The eEDM might be a probe to observe extended CP violation for which there exist numerous theories beyond the SM. Various experiments have been conducted, first focusing on atoms, but more recently the focus has shifted to molecules, where the effect of an eEDM on the quantum level structure is greatly enhanced. Besides ongoing experiments on YbF (Imperial College), ThO (ACME collaboration) and HfF^+ (Jila, Boulder) we have started an endeavor in the Netherlands to use BaF molecules as a probe [1]. While the P,T-odd enhancement factor for BaF is somewhat smaller than for the other target species [2] due to the fact that it is lighter (lower Z), this species is amenable to both laser cooling [3] and Stark deceleration, so that in principle longer coherence times could be achieved.

On the poster we will describe some of the recent activities and results on the preparation of a BaF eEDM experiment performed within a Netherlands based collaboration. A buffer gas cell-based slow molecular beam is built and characterized, and the Stark deceleration technique is demonstrated, on SrF molecules [4] and BaF molecules. In addition a novel spin-precession method is developed to analyze multi-level coherences between hyperfine levels in the ground state of barium monofluoride, in order to extract a constraint on an eEDM from long-term averaged data [5].

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Abstract ID : **111**

Study of Annihilations with Slow Extracted Antiprotons

Content

A number of experiments at CERN's Antiproton Decelerator aim to measure the properties of antihydrogen to find structural differences hinting at CPT symmetry breaking that would explain the observed baryon-antibaryon asymmetry in our universe. These experiments detect antihydrogen through annihilation making the antiproton-nucleus ($\bar{p}A$) annihilation one of the main processes of interest.

The Monte Carlo simulations of these events rely on physics models developed for high energies and theoretically extrapolated to lower energies. Previous measurements from the AD experiments, including the ASACUSA-Cusp collaboration show that the simulations do not reproduce the measured data. As even the annihilation mechanism itself is not well understood, a permanent beamline for slow extraction of sub-keV antiprotons is being set up at the ASACUSA facility, in order to measure the $\bar{p}A$ annihilation at rest for fifteen nuclei. The total multiplicity of the prongs and their kinetic energy distribution will be measured with a novel detection system using Timepix4 pixel detectors covering most of the solid angle. Individual annihilation events will be reconstructed by extrapolating the recorded pion tracks, revealing their angular distribution. This poster will give an overview of the experiment whose results will be implemented in a new simulation code for $\bar{p}A$ reactions.

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Track Classification: tests and extensions of the Standard Model of elementary particles

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Testing Lorentz Symmetry using Deuterium

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The Standard Model (SM) and the General relativity (GR) construct our best understanding of the fundamental forces of nature so far. There have been many effective field theory approaches, which try to close the gap between SM and GR at Planck Scale. However Planck scale suppression makes observable experimental signatures originating from such theories extremely tough to deal with. Based on effective field theory the Standard Model Extension (SME) [1] incorporates the SM and GR in the limit of vanishing Lorentz Symmetry and provides a basis for experimental and theoretical investigations of Lorentz symmetry violation [2].

Within SME framework the shifts in the hyper-fine energy levels in deuterium depend on the expo- nents of relative momentum of the proton in the deuteron core, which enhances the sensitivity to Lorentz and CPT violation for certain coefficients by 9- and even upto 18- orders of magnitude [3]. It also predicts the appearance of Lorentz violating signals at twice the sidereal frequency. These could be measured with transitions with $\Delta F \neq 0$. This poster would address the new spectrometer (Double split ring resonator [4, 5]) built for such measurements and the current experimental progress.

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Towards Precision Tests of Bound-state QED in U^{90+} Using Novel Metallic Magnetic Calorimeter Detectors

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Helium-like ions are the simplest atomic multi-body systems. Their study along the isoelectronic sequence provides a unique testing ground for the interplay of the effects of electron–electron correlation, relativity and quantum electrodynamics (QED). Especially heavy highly charged ions are ideal for testing higher-order QED terms. Their contributions are on the 1 eV level for transition energies of 100 keV. However, for ground state transitions in ions with nuclear charge $Z > 54$, where photons reach such energies, there is currently no data available with sufficient resolution and accuracy to challenge state-of-the-art theory [1]. In this context, the recent development of metallic magnetic calorimeter (MMC) detectors is of particular importance. Their high spectral resolution of a few tens of 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 experiments [2, 3].

First X-ray spectroscopy studies at the electron cooler of the low-energy storage ring CRYRING@ESR at GSI, Darmstadt have recently been performed for highly-charged ions [4, 5]. We report on the second campaign where MMC detectors have been used to study X-ray emission associated with the formation of excited helium-like uranium (U^{90+}) as a result of radiative recombination between stored U^{91+} ions and cooler electrons. The achieved spectral resolution of better than 90 eV at X-ray energies close to 100 keV enabled us to resolve the substructure of the $K\alpha_1$ and $K\alpha_2$ lines for the first time. This fivefold resolution improvement, compared to previous studies paves the way for future precision tests of strong-field QED and many-body effects.

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Towards Ramsey-Comb Spectroscopy of the 1S-2S Transition in He^+

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Precision spectroscopy of the 1S-2S transition in singly-ionized hydrogen-like helium is a promising avenue to test bound-state quantum electrodynamics. Additionally, combined with measurements on μHe^+ [1], nuclear size effects and the nuclear polarizability can be probed [2]. He^+ can be confined in a Paul trap and sympathetically cooled by laser-cooled Be^+, which also serves as the readout ion. Due to the strong binding of the remaining electron of He^+, the 1S-2S transition lies in the extreme ultraviolet (XUV) spectral range. We aim to measure this transition with 1 kHz or better accuracy using Ramsey-comb spectroscopy (RCS) [3], combined with high-harmonic generation (HHG) [4].

In RCS, two pulses (near 790 nm) from a frequency comb (FC) pulse train are selectively amplified to the mJ-level, upconverted to the XUV via HHG, and then used to do a Ramsey-type measurement by slightly scanning the repetition frequency of the FC. This is repeated for different pairs of (amplified) pulses of the FC, at different macro-delays that are equal to an integer times the repetition time of the FC. By combining Ramsey fringes measured at different macro-delays, we restore most of the good properties of the FC, almost as if the whole pulse train was employed for the excitation. An important difference with direct FC spectroscopy is that phase shifts which are constant for all fringes drop out of the analysis [5]. This includes the phase shifts from amplification, HHG, and the ac-Stark shift of the transition. Moreover, for a trapped He^+ ion, it will enable us to cancel the first-order Doppler shift by synchronizing the repetition frequency of the comb to the secular frequency of the helium ion. As a result, Doppler-free excitation will become possible with unequal photons, one at 790 nm, and one at its 25th harmonic (32 nm), which strongly enhances the excitation probability compared excitation with 2 times 60 nm.

We have recently shown the first excitation of the He^+ 1S-2S transition based on an atomic beam of helium and a focused beam of 32 nm and 790 nm. Due to the short transit time of the atoms in laser focus, a frequency-resolved RCS measurement is not possible in this geometry, but it allows us to characterize and tune our laser excitation scheme on a macroscopic sample of helium ions without the complications coming from single-ion trapping. This provides us with an excellent starting point to pursue frequency-resolved RCS on a single trapped helium ion. We are now working on installing the ion trap and characterizing the performance of the new Ramsey-comb laser system, based on an ultralow phase noise FC and a new home-built low-phase noise optical parametric amplifier. We will present the details of the 1S-2S excitation of He^+, and our progress towards the realization of RCS on a single trapped and sympathetically cooled He^+ ion.

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Two-loop self-energy corrections to the bound-electron g-factor: Status of M-term calculations

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The theoretical uncertainty of the bound-electron g-factor in heavy hydrogenlike ions is dominated by uncalculated QED Feynman diagrams with two self-energy loops. Precision calculations of these diagrams in which the interaction between electron and nucleus is treated exactly are needed to improve the theoretical accuracy of the bound-electron g-factor in the high-Z regime. Results of such calculations are highly relevant for ongoing and future experiments with high-Z ions as well as for an independent determination of fundamental constants such as the electron mass m_e and the fine structure constant α from the bound-electron g-factor [1]. Furthermore, comparisons of theory and experiment for heavy ions can serve as a probe for physics beyond the Standard Model after an improvement of the theoretical accuracy through the completion of two-loop calculations [2].

Due to the presence of ultraviolet divergences, two-loop self-energy Feynman diagrams need to be split into the loop-after-loop (LAL) contribution and the so-called F-, M- and P-terms which require different analytical and numerical techniques. The F-term corresponds to the ultraviolet divergent part of the nested and overlapping loop diagrams with free electron propagators inside the self-energy loops. The M-term 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. In our previous work, we have obtained full results for LAL and the F-term [3]. In this work, we present our results for the M-term contribution. P-term contributions correspond to diagrams which contain both bound-electron propagators inside the self-energy loops as well as an ultraviolet subdiagram and will be considered in a future work.

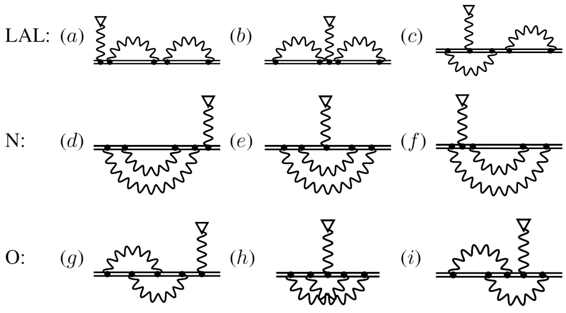

Figure 1: Furry-picture Feynman diagrams of the two-loop self-energy correction to the bound-electron g-factor.

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Variational Dirac–Coulomb approach with explicitly correlated basis functions

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The no-pair Dirac–Coulomb(–Breit) equation is solved with high-accuracy [1, 2, 3, 4] to provide a starting point for a new alternative theoretical method in relation with high-resolution atomic and molecular spectroscopy [5]. The sub-parts-per-billion convergence of the energy is achieved by considering the relativistic symmetry with an LS coupling scheme and expanding the relativistic wave function with an explicitly correlated Gaussian (ECG) basis set. The ECG significantly improves the description of the electron correlation compared to *e.g.,* a determinant basis set, but the positive-energy projection is more complicated due to the lack of the underlying one-electron picture. Therefore, several positive-energy projectors are examined to achieve and justify the parts-per-billion convergence of the energy. The no-pair Dirac–Coulomb energy is compared with perturbative results for atomic and molecular systems with small nuclear charge numbers and it reproduces the perturbative expressions [6] up to $\alpha^3 E_{\rm h}$ order.

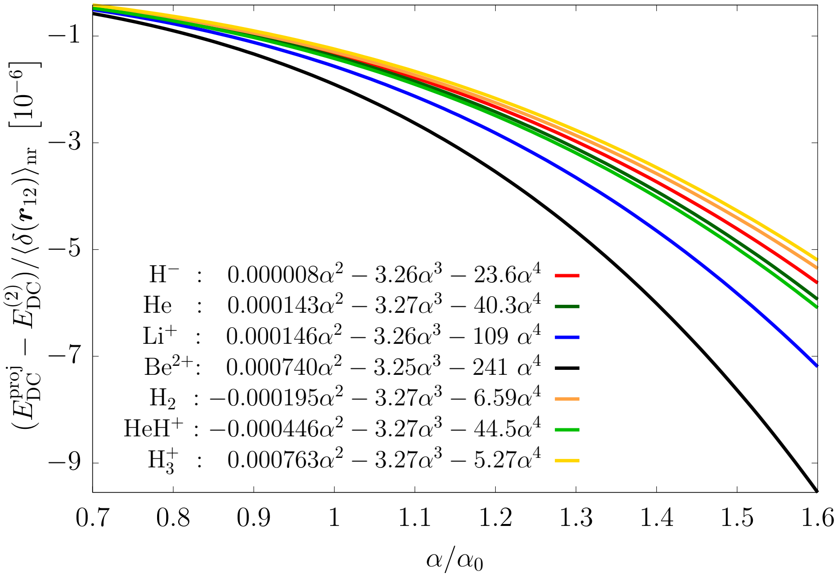

Figure 1: The dependence of the Dirac–Coulomb no-pair energy, ($E_{\rm DC}^{\rm proj}$) on the fine-structure constant (α). The non-relativistic energy and the α^2 perturbative energy correction ($E_{\rm DC}^{(2)}$) are extracted to highlight the agreement with the $\alpha^3 E_{\rm h}$ perturbative corrections, $\epsilon_{CC}^{++}\approx -3.24\langle\delta(\mathbf{r}_{12})\rangle_{\rm nr}\alpha^3 E_{\rm h}$ [6].

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LEMING: Towards the measurement of the gravitational acceleration of exotic muonium atoms

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A direct consequence of the CPT symmetry incorporated in the Standard Model (SM) is the equivalence of various measurable properties of matter and antimatter. However, with the lack of an unified theory between the SM and General Relativity (GR), the equivalence of the gravitational interaction of matter and antimatter cannot be taken for granted. The expected equivalence originates from the weak equivalence principle (WEP) which, among other measurables, implies the universality of free fall for all particles. However, this principle has so far only been rigorously tested with systems composed of first-generation matter particles.

The newly approved LEMING experiment at the Paul Scherrer institute aims to measure the free fall of muonium (Mu $= \mu^+ + e^-$), an exotic atom consisting purely of leptons: an anti-muon and an electron. Measuring the free fall of Mu atoms would be the first test of the WEP using elementary antimatter of the second generation and, additionally, using a system without large contributions to the mass from the strong interaction.

A direct free fall measurement is inherently challenging due to the short lifetime of Mu ($\tau \sim$ 2.2 μs). The experiment will utilize a three-grating atom interferometer, which requires a high-intensity, low-emittance Mu beam. This novel Mu source is being developed based on stopping accelerator muons in a layer of superfluid helium and converting them to a high quality in-vacuo Mu beam.

In this contribution the LEMING experiment is introduced. New measurements on the first observation of Mu emitted from superfluid helium and an initial characterization of the novel Mu source are presented. Implications of the newly developed Mu beam on the prospective gravity experiment will be discussed and the way towards a free fall experiment that would be the first direct measurement of gravitation interactions of (anti-)leptons will be described.

Development of Electrodes for the Muon Penning Trap Experiment

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At the J-PARC MLF/H-Line, an experiment to measure the fundamental properties of the muon by a Penning trap is planned. The final target precisions are 1 parts-per-billion for the magnetic moment and the mass, and 1 parts-per-million for the lifetime. A trapping electromagnetic field of a Penning trap is provided by a homogeneous magnetic field and a quandrupolar electrostatic potential. The experimental setup is shown in Fig.1. In this experiment, surface muon beams obtained at the J-PARC-MLF muon beamline H1 area are injected into the experimental apparatus to produce ultra-slow muonium, which is then laser-ionized to capture the ultra-slow muons at the electrodes center. Electrodes to produce the electric potential are therefore an essential component of this experiment. For the start of the experiment, we are designing and developing a box-shaped electrodes that enables the muon penning trap.

We have already designed the electrodes once and confirmed that the harmonicity of less than 20% can be achieved in the muon storage region inside the electrodes. Currently, for further harmonic improvement, we are creating a tool to optimize electrodes placement and voltage. In this presentation, we will report on the development status of the electrodes optimization tool and the latest design of the electrodes.

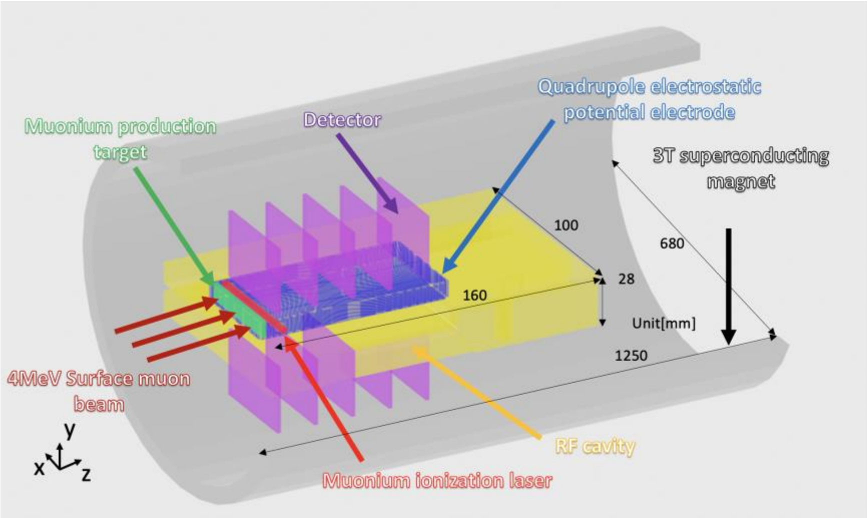

Figure 1: Schematic view of the Penning trap experiment of muons.

Doppler-free spectroscopy of an atomic beam probed in traveling-wave fields

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Precision spectroscopy based on atomic beams has achieved a number of remarkable advances in the last few decades. In these precision measurements, it's critical to reduce the Doppler effect. Common methods used to align the optical beams are the cat's eye method [1] and the active fiber-based retro-reflector method [2, 3]. Although the deviation angle ξ between two counter-propagating laser beams could be adjusted to below 10 μrad, the standing-wave field could induce some challenges, such as the assessment of residual Doppler shift, the systematic deviations from differences of the two counter-propagating laser beams, the detectable laser cooling effect on the atomic beams [4], and so on.

Here we propose a method to probe the precision spectroscopy of an atomic beam using traveling-wave laser beams. We demonstrated this method by measuring the $2^3S - 2^3P$ transition in a slow helium beam [5]. The first-order Doppler shift could be effectively suppressed by up to three orders of magnitude compared to that induced by the probing light beam. This method avoids using a standing-wave field when probing the spectra, reduces the laser power dependence, and eliminates the modulation due to the standing-wave fields. Preliminary measurements of the $2^3S - 2^3P$ transition of ^4He indicate that the uncertainty could be reduced to the sub-kHz level. Combined with the latest theoretical advances [6], we expect a new determination of the nuclear charge radius of the helium nucleus. This method could also be widely applied in various precision spectroscopy experiments based on atomic of molecular beams.

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Efficient evaluation of the non-linear vacuum polarization density in the finite basis Dirac problem

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In this work, we propose an efficient and accurate method to compute $\alpha\,(Z\alpha)^{n\geq 3}$ vacuum polarization density of hydrogen-like atoms, within the finite basis approximation of the Dirac equation. In order to prove the functionality of our computational method, we choose to work with the one-electron uranium atom. In summary, we find that the compliance to charge conjugation symmetry is necessary to obtain physical results that are in line with our knowledge of the analytical (exact) problem, as indicated in [1], in addition to Grant and Quiney in [2]. We also note that the final results are found to be in excellent agreement with previous formal analytical (and numerical) evaluations, done by Soff, Mohr and Plünien in [3, 4], as shown in figure (1). Our technique can be easily and efficiently implemented in codes that solve the radial Dirac equation in the finite basis set framework and could be employed for atomic problems with arbitrary (radial) nuclear charge distribution. The obtained numerical results of the non-linear vacuum polarization density are, therefore, automatically accounting for the extended nuclear size effect. This method is hence of special importance for atomic problems with nuclear distributions whose analytical expressions of their associated Dirac Green's functions are not in hand or have relatively complicated analytical forms.

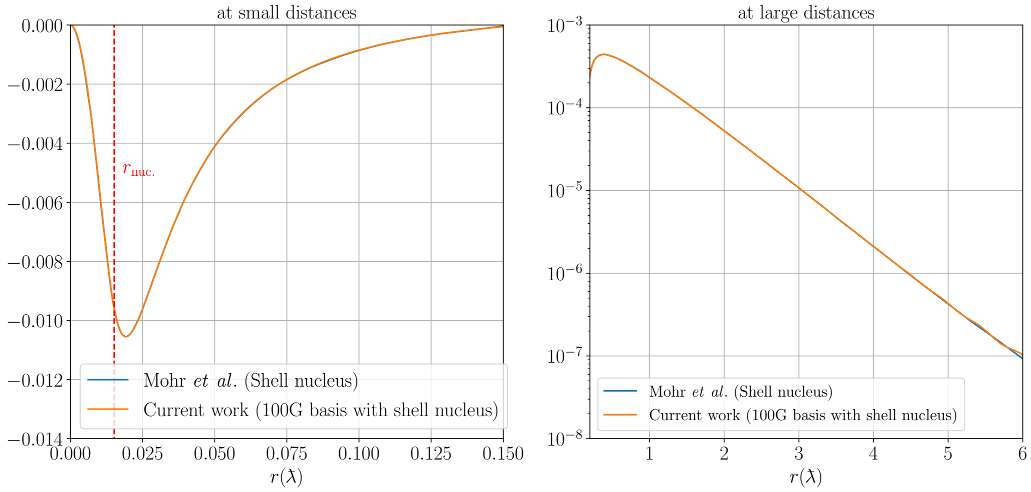

Figure 1: Non-linear VP density of a shell nucleus with $Z = 92$ and $r_{\text{nuc.}} = 5.86\,\text{fm}$.

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Experimental measurement of the energy dependence of the rate of muon transfer to oxygen at low energies

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We report the first experimental determination of the collision-energy dependence of the muon transfer rate from the ground state of muonic hydrogen to oxygen at near-thermal energies, based on the recent measurements of this transfer rate at temperatures in the range between 70 K and 336 K by the FAMU collaboration [1]. The FAMU experimental data were acquired at thermal equilibrium, and the observable temperature dependence of the transfer rate is related to the Laplace transform of the energy dependence. We resolve the strongly ill-posed inverse problem by combining a set of complementary approaches with established scattering theory results. A sharp increase of the muon transfer rate to oxygen by nearly an order of magnitude in the energy range 0 - 70 meV is found that is not observed in other gases. The results provide firm ground for the measurement of the hyperfine splitting in the ground state of muonic hydrogen and the determination of the Zemach radius of the proton by the FAMU collaboration [2].

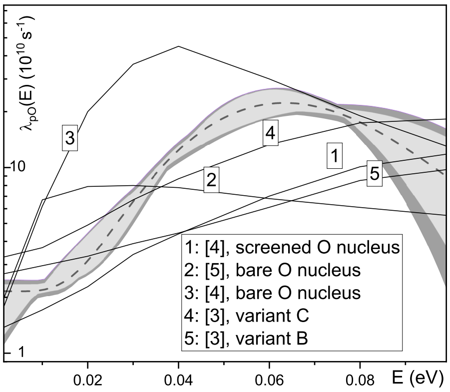

Figure: Comparison of the results of the advanced quantum-mechanical computations of the rate of muon transfer to oxigen in Refs. [3, 4, 5] with the energy dependence, experimentally determined in the present work (dashed) and its total uncertainty band composed of model (light-gray-shadowed) and statistical uncertainties (dark-gray), for $E < 100$ meV.

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Hydrogen Optical Lattice Clock

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Defining the values of constants is the best method to define units since it separates the definition from the realization. For example, there are two very different methods to realize the kg. In the future, there can be other methods of realizing the kg that adapt to possible advancements in technology without changing the definition. With the reform of the SI system, all but one of the units are now based on defined constants. The only remaining (natural) object is the cesium atom that is used to define and realize the SI second. A hydrogen lattice clock would allow us to complete the process and remove the last object from the SI system.

We propose a trap for atomic hydrogen that is not more complex than a usual optical atomic clock. It is based on a magic wavelength optical dipole trap, similar to the current most accurate optical clocks. The trap can be loaded without Doppler cooling which avoids an extremely difficult 121 nm laser. The $1S - 2S$ transition with a natural linewidth of 1.3 Hz would be the clock transition driven in a Doppler-free manner. Hence, only moderate temperature and no Doppler cooling are required. Our compact setup could be operated as a computable optical clock to redefine the SI-second as well as to improve spectroscopic data to test Quantum Electrodynamics.

Abstract ID : **104**

In-beam measurements of the hydrogen hyperfine splitting to constrain SME coefficients

Content

The ASACUSA-CUSP experiment located at CERN's antiproton decelerator aims at measuring the ground state hyperfine splitting of antihydrogen ($\bar{\mathrm{H}}$) using a beam technique to test CPT symmetry. For this purpose, a beam of cold (~50K) hydrogen has been developed to characterize the antihydrogen spectroscopy apparatus [1]. Beyond serving as a test bench for the $\bar{\mathrm{H}}$ experiment, the hydrogen beamline offers on its own a variety of possible measurements especially in the context of the Standard Model Extension (SME). The SME is an effective field theory that allows CPT and Lorentz symmetries to be broken [2]. A precise measurement of the hydrogen ground state hyperfine splitting was realized in 2017 using the extrapolation of a single hyperfine transition ($\sigma 1$) reaching a relative precision of 2.7 ppb [3]. Since then several additions to the setup were made allowing the precise measurement of the $\pi 1$ transition which provides sensitivities to some SME coefficients [4, 5]. A new measurement campaign on hydrogen started in 2022 and focused on $\pi 1$ precision measurements with swapping external magnetic fields using the $\sigma 1$ transition as a reference to constrain SME coefficients. An overview on the underlying theory and the experimental setup will be provided. The blind analysis of the collected data is effectively completed, and the contributions to the error budget, as well as peculiar effects originating from the static magnetic field, will be presented.

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Track Classification: tests and extensions of the Standard Model of elementary particles

Contribution Type: Poster presentation

Submitted by **NOWAK, Lilian** on **Wednesday, 10 May 2023**

Path integral formalism for radiative corrections in bound-state QED

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The theory of radiative corrections in bound-state quantum electrodynamics (QED) is developed using Feynman's path integral formalism[1,2]. As a first step, we derive the free Dirac propagator in spherical coordinates. Next, we derive the Dirac-Coulomb Green's function (DCGF) in the Furry picture by reducing it in a basis such that the effective action becomes similar to that of the nonrelativistic hydrogen atom. As such, the DCGF is obtained in closed form along with the energy spectrum of the bound states. In the final step, first-order Lamb shift, characterized by vacuum-polarization and self-energy shift, is calculated. The lowest-order vacuum polarization correction to the energy levels of bound electrons is calculated using perturbative path integral formalism. Starting from an interparticle classical action, we arrive directly at the propagators of QED. The energy level shifts are then calculated from the perturbative shift of poles of the Green's functions obtained. Finally, we derive the self-energy corrected propagator using Schwinger-Dyson equations through the path integral formalism. From the Feynman amplitude of this propagator, the energy shift is determined by complex contour integrals. The existing divergences are treated by separating the energy shift into zero-, one-, and many-potential terms following existing works [3,4]. The many potential term being UV-finite is calculated using partial-wave expansion, the zero- and one-potential terms are regularized using the regularized expressions for self-energy and vertex function in the momentum space and are evaluated numerically using b-spline codes[5].

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Abstract ID : **112**

Positron manipulation and control at ASACUSA

Content

The ASACUSA-Cusp experiment aims to perform spectroscopy of the hyperfine structure of antihydrogen by producing a beam of cold, spin polarised, ground state antihydrogen. The beam will be produced by mixing positrons and antiprotons in our unique Cusp trap which uses a pair of superconducting coils in an anti-Helmholtz configuration to produce a magnetic field capable of both confining the charged particles radially and polarizing the antihydrogen atoms.

Thus far, the collaboration has observed antihydrogen 2.7 m from the production region and measured the distribution of principal quantum number of these atoms. This weak beam was not suitable for the spectroscopy measurement so work commenced on improving the beam intensity and skewing the distribution towards ground state atoms. Simulations showed that the route towards this aim was producing colder dense positron plasmas.

Recently, a major technological milestone was achieved by the collaboration. Antihydrogen produced via three-body recombination will have an isotropic distribution so a large open solid angle is needed for the antiatoms to escape. This has the disadvantage that the production region is illuminated by a hot (300 K) black body. Previously, it has not been possible to cool plasma below 130 K, however, a new electrode stack and coldbore with a focus on blocking microwaves from the room temperature region has allowed particles to cool to 25 K maintaining the large open solid angle for the beam to escape.

In this presentation I will discuss the methods used by the ASACUSA Cusp experiment to manipulate and control positrons and give details on the most recent work on plasma handling and beam production in the new Cusp trap.

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Track Classification: spectroscopy of exotic atoms

Contribution Type: Poster presentation

Submitted by **Dr MURTAGH, Daniel James** on **Monday, 15 May 2023**

Complete one-loop contributions to the muon decay of U(1)$_z$ extensions of the standard model

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The theoretical prediction to the W-boson mass M_W is sensitive to physics beyond the standard model (BSM). Currently, there is a 2σ discrepancy between the standard model (SM) theoretical prediction and the measured value of M_W, obtained from the LEP 2 [1], Tevatron [2] and LHC [3] experiments. Considering also the recent measurement of M_W with the CDF II detector [4], the discrepancy is severely aggravated and the precise determination of theoretical BSM corrections is necessary. The parameter Δr [5], defined in the standard model (SM) as

$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_\mathrm{F}}[1+\Delta r]\,, \tag{1}$$

collects the radiative corrections to the muon decay process. It can be used to predict the mass M_W of the W-boson as a function of fiducial input parameters such as M_Z, α and G_F. We perform the one-loop renormalization of particle physics models with gauge sectors extended by an extra U(1)$_z$ symmetry in the on-shell renormalization scheme in order to compute the radiative corrections to the muon decay process. As a result we obtain – to the best of our knowledge for the first time in the literature a finite, gauge invariant prediction Δr_z. We generalize our findings to the $\overline{\mathrm{MS}}$ scheme and compare our predictions for M_W in U(1)$_z$ extensions to predictions of automated programs, such as `FlexibleSUSY` [6]. In the latter case corrections to the parameter

$$\hat{\rho}=\frac{M_W}{M_Z\hat{c}_\mathrm{W}} \tag{2}$$

are neglected, where the hat denotes $\overline{\mathrm{MS}}$ renormalized quantities and c_W is the cosine of the weak mixing angle. We also explore the parameter space of a U(1)$_z$ extension, the superweak extension of the SM [7] in order to find out whether the neglected terms in $\hat{\rho}$ become relevant.

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Precision Spectroscopy of Atomic and Molecular Negative Ions at the Frankfurt Low Energy Storage-Ring FLSR

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Negative ions are complex quantum systems in which an additional electron is bound to the neutral atom or molecule by a weak van der Waals force resulting from polarization of the electron shell. This binding depends strongly on the electron configuration of the shell and is therefore sensitive to electron correlation effects. Due to the lack of long ranged Coulomb force the resulting binding energies are small (typically around 1 eV) and exhibit rarely any excited states. Further there are almost no states with opposite parity and therefore lack of optically allowed transitions. The binding energy (electron affinity, EA) is typically the only accessible parameter in the spectroscopy of negative ions. The currently most precise measurement of the EA is by laser photodetachment threshold spectroscopy (LPT), where a narrow linewidth tunable laser is intersected with negative ions and the photon energy is scanned around the threshold, followed by detection of neutralized atoms.

Recently, the room-temperature electrostatic storage ring FLSR [1] at the University of Frankfurt was equipped with a source of negative ions and negative atomic and molecular ions have been successfully stored [2]. A high repetition-rate tunable Ti:sapphire laser pumped by a frequency doubled Nd:YAG laser developed at the University of Mainz has been installed and first photodetachment studies of O^- where performed. As a next step photodetachment studies of heavy atomic and molecular negative ions will be performed which will challenge state-of-the-art theoretical models. Results of the measurements will be presented and an outlook into future studies will be given.

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Progress on the Dirac Equation for the hydrogen molecular ion

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In the last few years, the spectroscopy of hydrogen molecular ions [1, 2] has advanced to a point where it can play a significant role in the determination of fundamental constants [3] and in placing tighter constraints on forces beyond the Standard Model [1, 4].

High-precision numerical resolution of the two-center Dirac Equation provides a path towards improving the theoretical predictions [5] via non-perturbative calculations of QED corrections. Major progress has been achieved recently, as the ground-state relativistic energy of H_2^+ was obtained with 20-digit accuracy [6, 7]. However, there is still room for improvement. In particular, calculations of QED corrections require evaluating the Dirac Green function, meaning that a numerical representation of the complete spectrum of the Dirac Hamiltonian has to be obtained. A method that gives one eigenstate at a time, such as the iterative method implemented in [6], would not be convenient for this purpose.

In this work [8], we write the Dirac Equation in a form suitable for complete diagonalization, which provides us with a numerical Green function. High-precision (27-32 digits) energy values are obtained using different kinetic balances. Furthermore, we were able to test our numerical Green function through the computation of relativistic sum rules, confirming that the representation of the Dirac spectrum is accurate and complete. The next step is the calculation of the one-loop self-energy correction.

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Tabletop Experiment for beyond Standard Model Physics: Cesium embedded in a Cryogenic Argon Matrix

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To explain the open questions in the fundaments of physics, new theories that reach beyond the standard model of particle physics are needed. A great number of these indirectly predict electric dipole moments (EDM) of fundamental particles in ranges that are just within reach for modern atomic and molecular physics experiments. While measurements in atomic and molecular beams, and more recently in ion traps, provided the most successful null measurements of the electron EDM over the past decades, only quite recently did the method of matrix isolation spectroscopy arise. It has the potential advantage of performing spectroscopy on unprecedented numbers of atoms/molecules at once. To perform such a measurement in the future, it is however necessary to first understand how the trapping of atoms inside the cryogenic matrix looks like in detail.

In this contribution, I would like to present what we learned so far through experiments and simulations and which future steps we are planning to take toward a measurement of the electron EDM and other beyond standard model effects.

Abstract ID : **109**

The SIDDHARTA-2 Experiment: Investigating the Strong Interaction with Kaonic Atoms

Content

The antikaon-nucleon interaction in the low-energy regime of QCD is, to this day, not fully understood and theoretical models need experimental constraints. Kaonic atoms are ideal candidates to study this regime of QCD including strangeness without the need for extrapolation to zero relative energy. The SIDDHARTA-2 experiment, located at the DAΦNE collider at LNF in Italy, can provide this input via X-ray spectroscopy of light kaonic atoms, in particular by measuring the $(2p \rightarrow 1s)$ transition in kaonic deuterium. In combination with the results for kaonic hydrogen obtained by SIDDHARTA, this will enable the extraction of the isospin-dependent antikaon-nucleon scattering lengths a_0 and a_1, which are crucial parameters for the theoretical descriptions. SIDDHARTA-2 performed its first periods of data acquisition in 2021 with a reduced setup, called SIDDHARTINO, and the full SIDDHARTA-2 setup in 2022. From these data, a new result for the $(3d \rightarrow 2p)$ transition in kaonic ^{4}He was extracted. Moreover, several transition energies in intermediate-mass kaonic atoms were measured for the first time. In preparation for the kaonic deuterium run, the setup was optimised via the implementation of a new SDD cooling system and additional veto detectors. The obtained results and optimisations of the apparatus are presented.

Primary author: TUECHLER, Marlene

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Theoretical hyperfine splittings of ^{7,9}Be^{2+} ions for future studies of nuclear properties

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The hyperfine structures of the $2\,^3S_1$ and $2\,^3P_J$ states of ^{7}Be^{2+} and ^{9}Be^{2+} are investigated within the framework of the nonrelativistic quantum electrodynamics (NRQED) [1], including relativistic and radiative corrections up to order $m\alpha^6$. Our results [2] are shown in Tables 1 and 2. The uncertainties of the calculated hyperfine splittings are on the order of tens of ppm, and for ^{9}Be^{2+} our results improve the previous theoretical and experimental values by at least two orders of magnitude. The improved sensitivity of the hyperfine splittings of ^{7,9}Be^{2+} to the nuclear Zemach radius and electric quadrupole moment opens the way to future measurements to extract the atomic physics values of these two nuclear properties to an accuracy of 5% or better.

Table 1: Theoretical hyperfine intervals in the $2\,^3S_1$ state of ^{7}Be^{2+} and ^{9}Be^{2+} with the Zemach radius $R_{\rm em} = 3.45(11)$ fm and $R_{\rm em} = 4.07(5)$ fm, respectively. The last column is the predicted accuracy of $R_{\rm em}$.

	$(J,F)-(J',F')$	ν (This work) cm^{-1}	Scholl *et al.* [3] cm^{-1}	$\lvert\delta R_{\rm em}/R_{\rm em}\rvert$ %
^{7}Be^{2+}	$(1,1/2)-(1,3/2)$	0.40952(1) at 24 ppm		5
	$(1,3/2)-(1,5/2)$	0.68250(1) at 15 ppm		3
^{9}Be^{2+}	$(1,1/2)-(1,3/2)$	0.344574(9) at 26 ppm	0.3448(10)	4
	$(1,3/2)-(1,5/2)$	0.574275(6) at 10 ppm	0.5740(11)	2

Table 2: Theoretical hyperfine intervals in the $2\,^3P_J$ state of ^{7}Be^{2+} and ^{9}Be^{2+} with the nuclear quadrupole moments $Q_d = -6.11$ fm^2 and $Q_d = 5.350(14)$ fm^2, respectively. The last column is the predicted accuracy of Q_d.

	$(J,F)-(J',F')$	$\nu(Q_d)$ (This work) cm^{-1}	Johnson *et al.* [4] cm^{-1}	Scholl *et al.* [3] cm^{-1}	$\lvert\delta Q_d/Q_d\rvert$ %
^{7}Be^{2+}	$(2,1/2)-(2,3/2)$	0.18726(1) at 53 ppm			4
	$(2,3/2)-(2,5/2)$	0.31574(1) at 32 ppm			5
	$(2,5/2)-(2,7/2)$	0.44953(1) at 22 ppm			4
	$(1,1/2)-(1,3/2)$	0.21130(1) at 47 ppm			3
	$(1,3/2)-(1,5/2)$	0.31346(1) at 32 ppm			5
^{9}Be^{2+}	$(2,1/2)-(2,3/2)$	0.158371(7) at 44 ppm	0.1581	0.1585(10)	3
	$(2,3/2)-(2,5/2)$	0.266123(4) at 15 ppm	0.2659	0.2659(11)	3
	$(2,5/2)-(2,7/2)$	0.377128(4) at 11 ppm	0.3773	0.3768(14)	2
	$(1,1/2)-(1,3/2)$	0.175126(4) at 23 ppm	0.1754	0.1751(10)	1
	$(1,3/2)-(1,5/2)$	0.265662(3) at 11 ppm	0.2654	0.2654(10)	2

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Theory of the magnetic moments and hyperfine splitting of ^{3}He$^+$

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In an external magnetic field, the ground state of the ^{3}He$^+$ ion is split into into four sublevels due to the combined hyperfine splitting and Zeeman effect. By measuring transition frequencies between these sublevels, it is possible to determine the g-factor of the bound electron, the ground-state hyperfine splitting as well as the shielded magnetic moment of the nucleus [1].

In this work, we present the theoretical calculations of the nuclear shielding constant, the ground-state hyperfine splitting and the bound-electron g-factor [2]. The theoretical uncertainty of the bound-electron g-factor is dominated by the uncertainty of the fine-structure constant α. This would allow an independent determination of α in future, provided that the experimental precision can be improved accordingly [3]. Combining the experimental value for the shielded nuclear magnetic moment and the theoretical value for the nuclear shielding constant, we extracted the magnetic moment of the bare nucleus with unprecedented precision, enabling new applications in magnetometry. Furthermore, we extracted the nuclear Zemach radius from the experimental hyperfine splitting value, in tension with the established literature value [4].

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Utilising the 1s-2s transition for a selective detection of hydrogen

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Key elements of the physics program of the Stefan Meyer Institute (SMI) are fundamental symmetries and searches physics beyond the Standard Model. In direct and indirect connection to the goal of hyperfine spectroscopy of antihydrogen at the AD of CERN within the ASACUSA collaboration, parallel experiments with hydrogen and deuterium are performed. Recently a high intensity ultraviolet laser has been acquired to enhance the detection capabilities in those experiments.

In this poster the experimental setup will be introduced including the laser system in a laser hut in the basement laboratory of SMI, the ion counting system and the atomic hydrogen beamline. First spectra demonstrating the selective detection of hydrogen will be shown.