FFK '2025

10th International Conference on Precision Physics and Fundamental Physical Constants

26-30 May 2025
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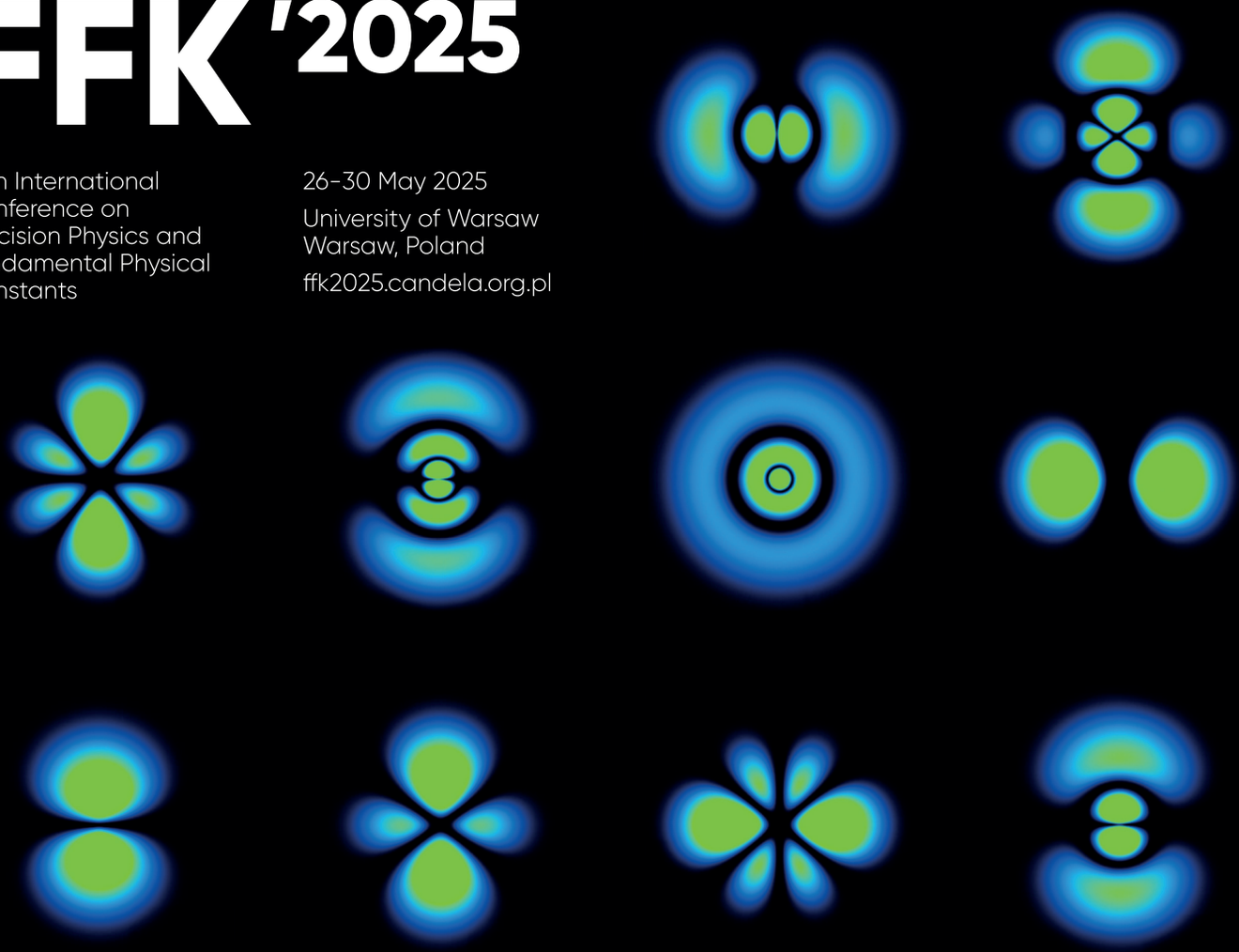

Book of Abstracts

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MONDAY

May 26th, 2025

Spectroscopy of the Hydrogen 2S-nS/D Transitions at Colorado State University

Dylan C. Yost [1, †], **Ryan G. Bullis** [1], **William L. Tavis** [1], **Michael R. Weiss** [1]
†corresponding author's email: dylan.yost@colostate.edu

Department of Physics, Colorado State University, Fort Collins, Colorado, 80523, USA

We will report on our ongoing measurements of the 2S-nS/D two-photon transitions in atomic hydrogen. The measurements feature a cryogenic ($\sim$ 5 K) beam of atomic hydrogen and preparation of the 2S state using the 1S-2S two-photon transition.

Previously, we had difficulty measuring transitions with natural linewidths below $\approx$ 500 kHz because the quickly varying light shifts as the atoms traversed the spectroscopy laser beam created distortions of the recovered lineshapes. Therefore, we had only previously measured the 2S-8$D_{5/2}$ transition with a natural linewidth of 572 kHz [1].

We have now introduced an auxiliary radiation field with a wavelength around 650 nm which is enhanced in the same optical cavity as the spectroscopy radiation. This additional field provides a nearly equal and opposite light shift which greatly mitigates the light shift. As shown in Fig. 1, this has allowed us to recover linewidths of $\approx$ 100 kHz for the 2S-nS transitions with $8 \leq n \leq 16$ [2]. The narrow recovered linewidths have provided for a valuable increase in our statistical signal to noise.

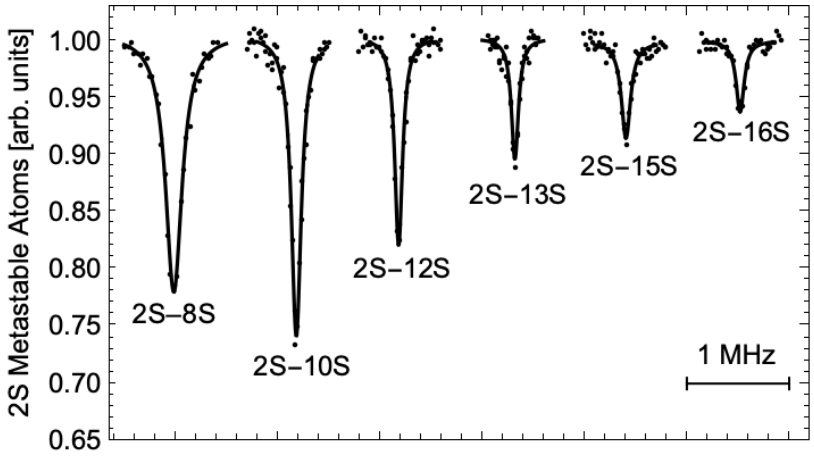

Figure 1: Recovered spectra for a selection of 2$S_{1/2}$-$nS_{1/2}$ two-photon transitions in atomic hydrogen with light shift mitigation. Spectra are obtained at different spectroscopy laser wavelengths but are plotted adjacent to one another for comparison.

We are now focused on characterizing systematic effects. Our new measurements feature active cancellation of stray electric fields, the ability to lower the temperature surrounding the spectroscopy region by around 50 K (to characterize shifts from blackbody radiation), and velocity characterization using a time-of-flight analysis. In addition, our ability to perform measurements on many 2S-nS/D transitions give us additional means to constrain possible systematic effects.

Acknowledgments

This research has been supported by the National Science Foundation (Grants PHY–2207298).

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1S-3S CW spectroscopy of Deuterium atoms

Pauline Yzombard [1], **Paul Martin** [1], **Lucile Julien** [1,], **François Biraben** [1], **François Nez** [1]

[1]Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS, Collège de France
†corresponding author's email: pauline.yzombard@lkb.upmc.fr

In this talk, I will begin by briefly presenting some of the key motivations for the spectroscopic study of hydrogen-like atoms, which serve as ideal tools for testing and challenging one of the most precise theories in physics: Quantum Electrodynamics (QED) [1]. I will then focus on the main experiment conducted in our Quantum tests with Hydrogen-like atoms group: the 1S-3S hydrogen spectroscopy experiment, performed at LKB (Paris) [2]. In particular, I will discuss the 1S-3S spectroscopy campaign on deuterium atoms that we conducted during the winter of 2020 using our home-built continuous-wave (CW) 205 nm laser. After addressing key systematic effects—including a newly identified one affecting our beamline—I will present the latest analysis results.

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Standard Model test below 1ppt with the 2S-6P transition frequency measurement in atomic hydrogen

Vitaly Wirthl[1, †], **Lothar Maisenbacher**[1,4], **Alexey Grinin**[1,5], **Arthur Matveev**[1], **Randolf Pohl**[2], **Theodor W. Hänsch**[1,3], **Thomas Udem**[1,3]

[1]Max-Planck-Institut für Quantenoptik, Garching, Germany
[2]Johannes Gutenberg-Universität Mainz, Mainz, Germany
[3]Ludwig-Maximilians-Universität München, München, Germany
[4]Present address: University of California, Berkeley, Berkeley, CA, USA
[5]Present address: Northwestern University, Evanston, IL, USA
†corresponding author's email: vitaly.wirthl@mpq.mpg.de

Quantum electrodynamics (QED) forms the basis for all other quantum field theories, upon which the Standard Model of particle physics is constructed. Due to the simplicity of the hydrogen atom, its energy levels can be precisely calculated from bound-state QED and confronted with the experiment. Such a comparison between theory and experiment is linked to the determination of fundamental constants, which enter the theory as parameters. Only if more indepedendent measurements are available than there are parameters, the theory can be tested. For hydrogen, the theory test mainly concerns the Rydberg constant and the proton radius. This requires at least two different transition frequency measurements to determine those, and more measurements to test the theory. Here we report on our 2S-6P transition frequency measurement with a relative uncertainty of 0.7 parts per trillion (ppt), a six-fold improvement over our previous measurement of the 2S-4P transition [1]. This result can be combined with the existing 1S-2S measurement [3] and the 2S-2P muonic hydrogen measurement [4]. We thereby determine the proton radius 2.5 times more accurate than the previous most accurate electronic hydrogen measurement [2] and provide a theory test with an accuracy below 1 ppt, making it one of the most precise tests of the Standard Model.

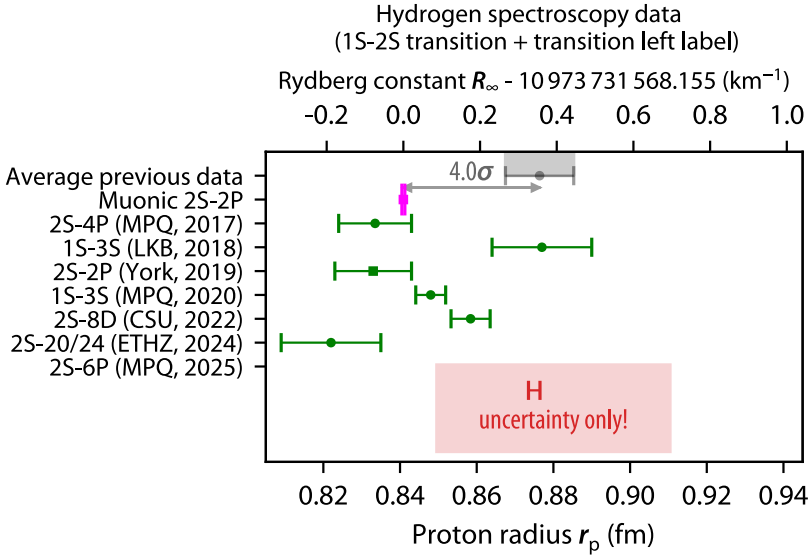

Figure 1: By combining the 1S-2S transition frequency measurement [3] with another transition measurement (left label), the proton radius and the Rydberg constant are determined. The theory test can then be pictured as a redundant determination of these constants. The muonic hydrogen measurement (magenta) [4] is discrepant with the average of all previous data before 2010 (grey). This discrepancy has been called the "proton radius puzzle". Since then more measurements have been done (green, e.g. [5]), where some inconsistencies remain. Our preliminary 2S-6P result in hydrogen with uncertainty shown in red (value will be presented in the talk) is six-fold more accurate that our previous 2S-4P measurement [1], 2.5 times more accurate than our 1S-3S measurement [2], and allows the most accurate theory test in hydrogen to date.

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The fine and hyperfine structure of molecular hydrogen ions from spectroscopy of Rydberg states

Ioana Doran [1,†], **Leon Jeckel** [1], **Maximilian Beyer** [2], **Christian Jungen** [3], **Frédéric Merkt** [1]

[1]Institute of Molecular Physical Science, ETH Zürich, Switzerland
[2]Department of Physics and Astronomy, Vrije Universiteit, Amsterdam, The Netherlands
[3]Université Paris-Saclay, Centre National de la Recherche Scientifique, Laboratoire Aimé Cotton, Orsay, France
†corresponding author's email: ioana.doran@phys.chem.ethz.ch

Precision measurements of spin-rovibrational energies in molecular hydrogen ions provide access to fundamental constants such as the proton-to-electron mass ratio or the proton charge radius, by comparison with theoretical results [1, 2, 3]. These ionic energy intervals can be determined precisely by Rydberg-series extrapolation [4, 5] of series converging to different spin-rovibrational states in the ion. Measurements of Rydberg-Stark manifolds at varying electric field strengths and comparison with precise calculations of the field-induced Stark shifts [6] enable the determination of the zero-quantum-defect positions $-R_{H_2}/n^2$, which yield precise ionization thresholds. The use of this procedure has recently been demonstrated in determining the fundamental vibrational interval of H_2^+ with sub-MHz uncertainty [7].

This contribution focuses on the extension of the zero-quantum-defect method to molecular hydrogen ions which have a fine or hyperfine structure. We present precision measurements and calculations of Stark manifolds in Rydberg states of molecular hydrogen including interactions involving the rotational angular momentum and the nuclear spin of the ion. Focusing on the spin-rotation splitting in para-H_2^+ ($v^+ = 1, N^+ = 2, I = 0$) and the hyperfine splitting in ortho-D_2^+ ($v^+ = 1, N^+ = 0, I = 0, 2$), we show that these calculations accurately describe the experimentally measured Rydberg-Stark manifolds quantitatively. Finally, the comparison between experiment and calculations is used to determine the hyperfine splitting in ortho-D_2^+ with an uncertainty in the low-kHz range.

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Accurate spectroscopy of cold hydrogen molecules

Piotr Wcisło

Institute of Physics, Faculty of Physics, Astronomy and Informatics,
Nicolaus Copernicus University in Toruń, Grudziądzka 5, 87-100 Toruń, Poland
piotr.wcislo@fizyka.umk.pl

Due to its simplicity, H_2 constitutes a perfect tool for testing fundamental physics: testing quantum electrodynamics, determining fundamental constants, or searching for new physics beyond the Standard Model. H_2 has a huge advantage over the other simple calculable systems of having a set of a few hundred ultralong living rovibrational states, which implies the ultimate limit for testing fundamental physics with H_2 at a relative accuracy level of 10^{-24}. The present experiments are far from this limit.

I will present our cavity-enhanced spectrometer fully operating in the deep cryogenic regime down to 4 K [1]. We solved several technological challenges that allowed us to uniformly cool not only the sample but also the entire cavity, including the mirrors and cavity length actuator [2], which ensures the thermodynamic equilibrium of a gas sample. I will present our first experimental results on accurate determination of the energy of the 1-0 S(0) transition in H_2 [1]. I will also present our so far results of an ongoing project aimed at trapping cold H_2.

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Precision spectroscopy of atomic helium and molecular hydrogen at Hefei

Shui-Ming Hu †

University of Science and Technology of China, Hefei 230026, China †corresponding author's email: smhu@ustc.edu.cn

Atomic helium and molecular hydrogen are the simplest neutral systems after atomic hydrogen. Their energy levels and properties can be calculated precisely based on the quantum electrodynamics (QED) theory and several fundamental constants. In this talk, we present our recent progress on precision measurements of these two systems.

The post-selection (PS) effect was investigated in high-precision spectroscopy of the $2^3S - 2^3P$ transition of ^{4}He using an atomic beam. This effect induces a shift in the measured transition frequency of up to –55 kHz. After correcting for the PS shift, we obtain a transition frequency of $276,764,094,712.45 \pm 0.86$ kHz for the $2^3S_1 - 2^3P_0$ transition [1]. This result, combined with the existing data for ^{3}He, was used to extract the difference in the squared nuclear charge radii between the ^{3}He and ^{4}He nuclei. A new precision measurement of the $2^3S_1 - 2^3P$ transition of ^{3}He is currently underway.

In the past decade, the precision of transition frequencies for molecular hydrogen, including H_2 and HD, has been significantly improved to the 10–100 kHz level. Beyond transition frequencies, other molecular properties can also serve as valuable tests for theoretical models and computational methods. Recently, we measured the electric polarizability of the H_2 molecule with an uncertainty at the 10^{-5} level [2], which agrees well with the theoretical predictions. Additionally, we measured [3] the line intensity of the Q(1) line in the (2–0) vibrational band of H_2 near 1.24 μm with an uncertainty of less than 0.1%, and compared the results with theoretical calculations [4, 5]. These measurements provide a solid foundation for further improvements in the near future, and the techniques used are applicable to other molecular systems as well [6, 7].

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The ^{3}He charge radius and the ^{3}He-^{4}He isotope shift from laser spectroscopy of muonic He ions

Randolf Pohl [1, †] for the CREMA Collaboration

[1] **Physics Department, University of Mainz, Germany**

†corresponding author's email: pohl@uni-mainz.de

Hydrogen-like light muonic ions, in which one negative muon replaces all the electrons, are extremely sensitive probes of nuclear structure, because the large muon mass increases tremendously the wave function overlap with the nucleus. Using pulsed laser spectroscopy we have measured three 2S-2P transitions in the muonic helium-3 ion (μ^3He$^+$), an ion formed by a negative muon and bare helium-3 nucleus. This allowed us to extract the Lamb shift, the 2P fine structure splitting, and the 2S-hyperfine splitting in μ^3He$^+$ [1] Comparing these measurements to theory we determine the rms charge radius of the helion (^{3}He nucleus) to be r_h = 1.97007(94) fm, in good agreement with the value from elastic electron scattering, but a factor 15 more accurate. We determine the ^{3}He-^{4}He (squared) charge radius difference of $\delta r^2 = 1.0636(6)_\mathrm{exp}(30)_\mathrm{theo}\mathrm{fm}^2$, in excellent agreement with recent measurements in ordinary helium atoms [2, 3]. Our results represent benchmarks for few-nucleon theories and open the way for precision QED tests in He atoms and ions.

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

Elmer Gründeman [1,2, †]
On behalf of the CREMA collaboration

[1] Institute for Particle Physics and Astrophysics, ETH Zürich, Otto-Stern-Weg 5, 8093 Zürich, Switzerland
[2]Center for Neutron and Muon Sciences, Paul Scherrer Institute, 5232 Villigen, Switzerland
†corresponding author's email: egruendeman@phys.ethz.ch

Laser spectroscopy of muonic hydrogen (μp) is an ideal platform to probe the proton structure. At the Paul Scherrer Institute, the CREMA collaboration aims to measure the ground-state hyperfine splitting (1S HFS) with a relative accuracy of about 1×10^{-6} to infer the proton structure contribution with a relative uncertainty of about 1×10^{-4}. For this measurement, we are developing a pulsed laser system with the aim of delivering 3 mJ pulses at a wavelength of 6.8 µm stochastically triggered by the arrival of muons. We report on the measurement principle and the current status of the hardware development.

The FAMU Experiment: Measuring the Hyperfine Splitting of Muonic Hydrogen in the Ground State

Emiliano Mocchiutti [1, †] on behalf of the FAMU Collaboration

[1]Sezione INFN di Trieste, via A. Valerio 2, Trieste, Italy
†corresponding author's email: Emiliano.Mocchiutti@infn.it

The FAMU experiment (Fisica degli Atomi MUonici) aims to measure the hyperfine splitting of the ground state of muonic hydrogen. This measurement provides precise insights into the proton's magnetic structure, plays a crucial role in validating high-precision QED calculations, and tests the fundamental interaction between the proton and the muon. From this measurement, the Zemach radius of the proton can be estimated with an accuracy better than 1%.

The experiment is conducted at the ISIS facility of the Rutherford Appleton Laboratory (UK), specifically at the RIKEN Port1 beamline.

The experimental method relies on exciting the hyperfine splitting using a laser system and detecting the resulting increase in characteristic X-rays from muonic oxygen. This increase occurs due to the enhanced probability of muon transfer to an oxygen atom following the recoil de-excitation of the muonic hydrogen atom.

The X-ray detection system is designed to identify an increase in the characteristic X-rays of muonic oxygen following laser injection into the target. To achieve precise measurements, the detection apparatus must combine excellent timing performance with high energy resolution. The system consists of 34 cesium-enriched lanthanum bromide crystals, with 6 read by photomultiplier tubes and the remaining 28 by silicon photomultiplier arrays.

The pulsed laser used in the experiment, specifically developed by INFN Trieste for this application, is unique worldwide due to its tunability, energy, and spectral purity, key parameters for the success of the experiment. The transition of interest, expected around 183 meV, requires a laser operating in the mid-infrared region at approximately 6.78 μm. It must be capable of extremely precise and stable tuning to the target wavelength over an extended period.

The experiment began data collection in 2023, and four data-taking periods have been completed so far. Additional measurement periods are planned for 2025.

This presentation will provide an update on the current status of the experiment, its performance, and progress in data analysis.

TUESDAY

May 27th, 2025

Precision Penning-trap mass measurements of light atomic masses

K. Blaum

Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany

Precision Penning-trap mass measurements contribute to a number of physics questions in atomic, nuclear, neutrino and fundamental physics. They allow, among others, for the determination of fundamental constants, to perform stringent tests of bound-state quantum electrodynamics calculations and serve as a systematic check in experiments aiming for the determination of the absolute mass scale of neutrinos, e.g., with the Karlsruhe Tritium Neutrino Experiment KATRIN. I will present our most recent mass measurements in the regime of light ions, which allowed to resolve discrepancies in the reported literature masses of light atomic nuclei from various experiments, as well as of heavier species for neutrino physics input and even for dark matter searches where relative mass uncertainties at the level of 10-12 are required.

Exploring Fundamental Constants with High-Precision Spectroscopy of Molecular Hydrogen Ions

Soroosh Alighanbari [1, †], **Magnus R. Schenkel** [1], **Vladimir I. Korobov** [2], **Jean-Phillipe Karr** [3], **Stephan Schiller** [1]

[1]Institut für Experimentalphysik, Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany
[2]Bogoliubov Laboratory of Theoretical Physics, Joint Institute for Nuclear Research, 141980 Dubna, Russia
[3]Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS, Université PSL, Collége de France, 75005 Paris, France and Université d'Evry-Val d' Essonne, Université Paris-Saclay, 91000 Evry, France
†corresponding author's email: soroosh.alighanbari@hhu.de

Molecular hydrogen ions (MHIs) are the simplest molecules; they have significant potential for refining our understanding of fundamental physics, e.g. novel tests of CPT invariance, search for new physics, and determination of fundamental constants (FCs). So far, the heteronuclear HD^+ has been the most intensively studied, providing precise data on rovibrational transitions. These have been found to be in good agreement with ab initio predictions, with a few exceptions [1]. Extending the investigations to other isotopologues brings new challenges, particularly with homonuclear MHIs, that present difficulties for laser spectroscopy due to the absence of electric-dipole transitions. We have succeeded in measuring an electric-quadrupole (E2) rovibrational transition in H_2^+, demonstrating the first vibrational laser spectroscopy of H_2^+ [2]. We have also performed a Doppler-free spectroscopy campaign of H_2^+ and measured two spin components of a first-overtone rovibrational transition. We determined the spin-averaged transition frequency and, in combination with precise theoretical predictions, derived an independent value for the proton-electron mass ratio. The value is consistent with the recent CODATA 2022 value [3] and the uncertainty is comparable, see Fig. 1. This work marks a step towards testing CPT invariance through a comparison of a vibrational transition in H_2^+ with that of its antimatter counterpart, anti-H_2^+ [4, 5]. A long-term perspective for MHI spectroscopy involves measuring a moderately large set of transitions for all or nearly all MHI isotopologues (H_2^+, D_2^+, T_2^+, HD^+, HT^+, DT^+) with 1-Hz experimental uncertainties. The combination of such precise measurements with future improved theoretical predictions and H/D data could significantly reduce the uncertainties of m_p/m_e, m_d/m_e, m_t/m_e, and of the triton charge radius, compared to those of CODATA 2022. From this data of purely electronic systems, additionally, proton and deuteron radii could be determined with uncertainties comparable to those of CODATA 2022, thereby enabling a test of lepton universality.

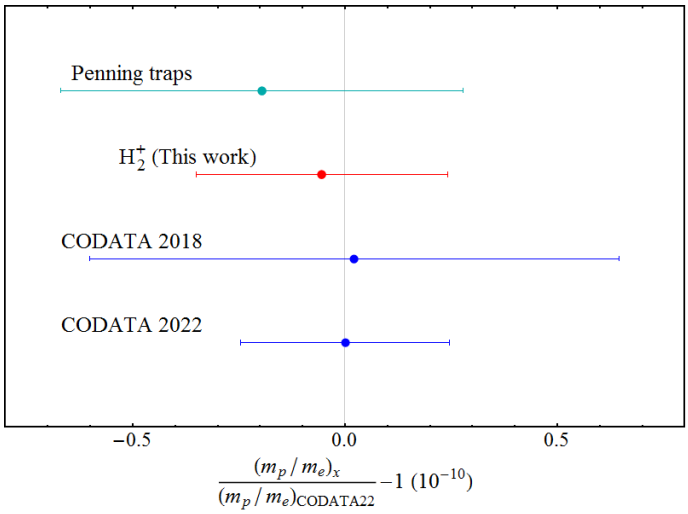

Figure 1: The proton-to-electron mass ratio relative to the CODATA 2022 value. The CODATA 2018 value did not include the results from MHI spectroscopy, whereas these results are incorporated into the CODATA 2022 value.

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Precision Spectroscopy of Molecular Hydrogen Ions in the ALPHATRAP Penning trap

Sven Sturm[1, †]

[1]Max Planck Institute for Nuclear Physics, Saupfercheckweg 1, 69117 Heidelberg, Germany
†For the ALPHATRAP MHI spectroscopy collaboration.
Corresponding author's email: sven.sturm@mpi-hd.mpg.de

Experiments with single ions confined in a Penning trap enable access to a broad range of observables that are of fundamental importance for our understanding of fundamental physics. In the magnetic field of the trap, the cyclotron frequency of an ion can be determined with unique precision and gives direct access to the charge-to-mass ratio or alternatively the precise magnetic field strength. We have determined a number of fundamental parameters, such as the electron, proton, neutron and deuteron [1] atomic masses with leading precision . Further, we can non-destructively determine a bound electron's spin state via the continuous Stern-Gerlach effect in a magnetic bottle. This way, we get access to the (Larmor) spin precession frequency and so are able to determine the g-factors of atomic and molecular ions.

Molecular hydrogen ions (MHI) H_2^+ and its isotopologues (HD^+ and D_2^+ and HT^+) have a rich rovibrational structure. The relative simplicity of these molecules enables precise theoretical calculations, giving access to fundamental constants such as the mass ratios of the electron and the proton, deuteron and triton. At ALPHATRAP [2] we have developed a complete toolset that enables full control of the rovibrational and hyperfine state of MHI, taking advantage of the dependence of the electron spin transition frequency on the particular internal quantum state [3]. Since this technique does not require a co-trapped auxiliary ion, it is a seminal step towards a possible future spectroscopy of the antimatter equivalent, $\bar{H}_2^-$, which could enable a unique test of charge-parity-time (CPT) reversal symmetry. Our cryogenic vacuum valve enables the required extremely good vacuum conditions, while allowing the injection of external ions.

In a first step, we have precisely measured the hyperfine structure in the ground-state of HD^+ and so have tested the theory prediction [4]. Currently, we are performing precision laser spectroscopy of a ro-vibrational transition in a collaboration with the Schiller group from HHU Düsseldorf.

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Hydrogen molecular ions: status of theory

Jean-Philippe Karr [1,2] †

[1]Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS-Université PSL, Collège de France, 4 place Jussieu, F-75005 Paris, France
[2]Université Evry Paris-Saclay, Boulevard FranMitterrand, F-91000 Evry, France
†corresponding author's email: jean-philippe.karr@lkb.upmc.fr

Thanks to impressive progress in experimental accuracy, spectroscopy of the HD^+ molecular ion has contributed to improved determinations of mass ratios, such as m_p/m_e, in the latest CODATA adjustment [1, 2]. The precision of these measurements can be expected to improve further in the next few years. Moreover, efforts have been recently extended to H_2^+ [3, 4], and spectroscopy of single HD^+ ions in a Penning trap offers the possibility of measuring hyperfine intervals and the bound-electron g-factor [5].

I will describe the current status of theory and ongoing work on the spin-averaged energy levels [6], hyperfine structure [7], and electronic g-factor [8].

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The ionization energy of metastable ^{3}He and ^{4}He ($2\,^3S_1$) and the alpha- and helion-particle charge-radius difference from precision spectroscopy of the np Rydberg series

Gloria Clausen[1] **and Frédéric Merkt**[1, †]**,**

[1]*Institute of Molecular Physical Science, ETH Zurich*
†corresponding author's email: frederic.merkt@phys.chem.ethz.ch

The comparison of calculated and experimental energy intervals in He represents an attractive route to test the fundamental theory of two-electron systems and to determine physical constants and particle properties such as the charge radii of the helion ($^3He^{2+}$) and alpha ($^4He^{2+}$) particles. This route is, however, currently blocked by discrepancies between experimental and theoretical results in this fundamental atomic system. In particular, calculated and measured values of the transition frequencies from the $2\,^3S_1$ metastable and the $2\,^3P_0$ states of ^{4}He to the $3\,^3D_1$ state differ by more than 10σ [1, 2, 3] and experimental and theoretical values of the ionization frequency of the $2\,^3S_1$ and $2\,^1S_0$ metastable states of ^{4}He differ by 9σ [1, 4, 5]. Moreover, recently reported $^3He^{2+}$ and $^4He^{2+}$ squared-charge-radii differences obtained by combining theory and precision spectroscopy for $2\,^2P \leftarrow 2\,^2S$ transitions in muonic He^+ ions [6] and for the isotopic shift of the $2\,^3S_1 \leftarrow 2\,^1S_0$ transition [7] in He deviate by 3.6σ. Recent progress in the theoretical treatment of singlet-triplet mixing in ^{3}He might resolve this discrepancy [8, 9].

In this talk, we present an improved experimental method for the determination of the ionization energy of the $2\,^3S_1$ state of ^{4}He via the measurement of transitions from the $2\,^3S_1$ state to np Rydberg states. The upgrades to our experiment include (i) the preparation of a cold, supersonic expansion of helium atoms in the $2\,^3S_1$ state, (ii) the development of a laser system with SI-traceable frequency calibration for driving the transitions to np Rydberg states, (iii) the implementation of a sub-Doppler, background-free detection method [10], and (iv) an interferometric alignment procedure for counter-propagating laser beams to cancel the 1st-order Doppler shifts [5]. We illustrate the power of this method with a new determination of the ionization energy of $2\,^3S_1$ metastable ^{4}He [$E_I(^4\mathrm{He})/h$ = 1 152 842 742.7082(55)$_{stat}$(25)$_{sys}$ MHz] with a fractional uncertainty of $4 \cdot 10^{-12}$ by extrapolation of the np series.

These measurements were recently extended to precision measurements of hyperfine-resolved transitions from the $2\,^3S_1$ metastable state of ^{3}He to high np Rydberg states converging on the $F^+ = 0, 1$ hyperfine levels of the $^3He^+$ $1s\,^2S_{1/2}$ ground state. Rydberg-series extrapolation using multichannel quantum-defect theory (MQDT) enabled the determination of the ionization energy of the $2\,^3S_1$ state of ^{3}He [$E_I(^3\mathrm{He})/h$ = 1 152 788 844.6154(77)$_{stat}$(25)$_{sys}$ MHz] and of the corresponding isotopic shift [$(E_I(^4\mathrm{He}) - E_I(^3\mathrm{He}))/h$ = 53 898.093(9) MHz]. The MQDT analysis also permitted the quantification of singlet-triplet mixing in the np series induced by the hyperfine interaction. From the isotopic shift of the ionization energy of He, the difference δr^2 between the squared charge-radii of the helion and alpha particles was determined to be 1.060(10) fm^2.

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QED theory of isotope shift

Krzysztof Pachucki [1], **Vojtěch Patkóš** [2, †], **Vladimir A. Yerokhin** [3]

[1]Faculty of Physics, University of Warsaw, ul. Pasteura 5, 02-093 Warszawa, Poland
[2]Faculty of Mathematics and Physics, Charles University, Ke Karlovu 3, 121 16 Prague 2, Czech Republic
[3]Max–Planck–Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany
†corresponding author's email: vojtech.patkos@matfyz.cuni.cz

The isotope shift is defined as the difference of the transition frequencies of different isotopes of the same element, averaged over all fine and hyperfine sublevels. A remarkable feature of the isotope shift is that the relative contribution of the finite nuclear size effect to it is much larger than that to the transition energies. Because of this, the isotope shift is particularly suitable for determination of the nuclear charge radii differences. Theoretical description of the isotope shift is simpler in comparison to the energy levels since only restricted set of operators contribute to it [1].

Interestingly, conflicting results for the nuclear charge radii differences were obtained from various transitions and experiments [2]. Namely, the helion-alpha particle charge radii differences obtained from ordinary and muonic helium were in 3.6σ disagreement with each other [3, 4]. Recently, it was pointed out that the second-order hyperfine correction was underestimated and the mixing with higher excited states brought the two results into a better agreement [5]. In our paper [6] we calculated the complete second-order hyperfine correction and shown that the results from ordinary and muonic helium are in very good agreement. Here, we will present these results and the current status of QED theory of isotope shift.

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Efficient calculation of electron vacuum polarization contributions to energy levels of two-body muonic atoms and ions

Gregory S Adkins [1, †], **Ulrich D. Jentschura** [2],

[1]Department of Physics and Astronomy, Franklin & Marshall College, Lancaster, Pennsylvania, 17604, USA
[2]Department of Physics and LAMOR, Missouri University of Science and Technology, Rolla, Missouri, 65409, USA
†corresponding author's email: gadkins@fandm.edu

Electron vacuum polarization gives the dominant correction to the energy levels of muonic atoms such as muonic hydrogen and muonic deuterium. In this talk, we present new tools that simplify the calculation of vacuum polarization corrections and lead to improved precision. Specific developments include a convenient form for the three-loop irreducible vacuum polarization correction based on a recent analytic calculation of the three-loop spectral density [1, 2] and new analytic expressions for a number of the integrals that occur in vacuum polarization calculations. Analytic results are given for the one-loop and some of the two- and three-loop corrections that are valid for all states.

Acknowledgments

This work was supported by the U.S. National Science Foundation through Grants PHY-2308792 (G.S.A.) and PHY–2110294 (U.D.J.), and by the U.S. National Institute of Standards and Technology Grant 60NANB23D230 (G.S.A.).

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Recent developments in hydrogen Lamb shift and Rydberg constant

Vladimir A. Yerokhin

Max-Planck Institute for Nuclear Physics, Saupfercheckweg 1, 69117 Heidelberg, Germany

I discuss recent progress achieved in theoretical calculations of the Lamb shift in hydrogen and the implications for the determination of the Rydberg constant. Particular attention is paid to one of the most problematic effects, the two-loop electron self-energy. The corresponding correction in hydrogen is obtained by combining numerical all-order (in $Z\alpha$) and $Z\alpha$-expansion calculations [1-3]. Recently, we were able to achieve a breakthrough in all-order calculations of the electron self-energy [4], basing on the method for improving convergence of the partial-wave expansion suggested in [5]. Extrapolation of our all-order results to hydrogen yields a result twice as precise as the previously accepted value [6], differing from it by 2.8 standard deviations. The resulting shift in the theoretical prediction for the 1S-2S transition frequency in hydrogen decreases the value of the Rydberg constant by one standard deviation.

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Improvement of the bound-electron g-factor theory after completion of two-loop self-energy calculations

Bastian Sikora [1, †], **Vladimir A. Yerokhin** [1], **Zoltán Harman** [1], **Christoph H. Keitel** [1]

[1]Theory Division, Max Planck Institute for Nuclear Physics, Saupfercheckweg 1, 69117 Heidelberg, Germany
†corresponding author's email: bastian.sikora@mpi-hd.mpg.de

The bound-electron g-factor in highly charged ions can be measured and calculated with high precision. In a recent collaborative project, the experimental and theoretical g-factors of the bound electron in the hydrogenlike tin ion were found to be in excellent agreement with one another [1]. However, the theoretical uncertainty given in that work was orders of magnitude larger than the experimental uncertainty, due to uncalculated two-loop QED binding corrections.

In our new work, we report the completion of the calculation of QED Feynman diagrams with two self-energy loops (SESE correction) contributing to the bound electron's g-factor, taking into account the electron-nucleus interaction exactly [2]. This all-order evaluation required the total SESE correction to be split into the so-called LAL contribution and the F-, M- and P-terms which all require different analytical and numerical techniques. In our previous work, we had presented numerical results for the LAL contribution and the F-term, demonstrating that our calculations are consistent with established free-electron results [3]. With the completion of M- and P-terms, we demonstrate that our results allow a significant improvement of the total theoretical uncertainty of the g-factor in the high-Z regime [2].

Our calculations will enable improved tests of QED in planned near-future g-factor measurements at ALPHATRAP in Heidelberg and ARTEMIS in Darmstadt, and are relevant for the determination of fundamental constants as well as enhanced searches for New Physics using heavy highly charged ions.

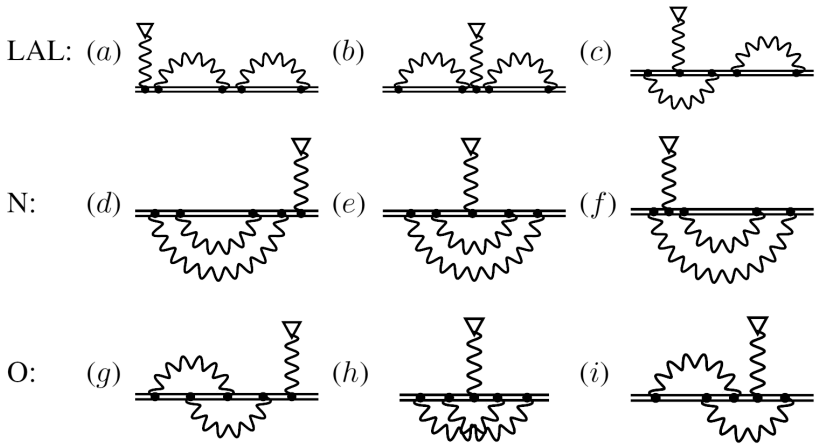

Figure 1: Feynman diagrams with two self-energy loops contributing to the bound-electron g-factor

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Fundamental Constants and Tests of QED Theory via the Bound Electron *g*-factor

Matthew Bohman[1, †], **Fabian Heiße**[1], **Charlotte König**[1], **Jialin Liu**[1], **Jonathan Morgner**[1], **José Ramon Crespo López-Urrutia**[1], **Sven Sturm**[1], **and Klaus Blaum**[1]

[1]Max-Planck-Institut für Kernphysik, 69117 Heidelberg, Germany
†corresponding author's email: matthew.bohman@mpi-hd.mpg.de

The *g*-factor of an electron, bound to a bare nucleus or few-electron atomic system, can be calculated to high precision in the framework of quantum electrodynamics (QED) - providing a highly stringent test of the Standard Model of particle physics when it is measured to similarly high precision. The cryogenic precision Penning-trap platform is very well-suited to study such system as it provides not only long-term recombination-free storage of these these systems, a crucial requirement for highly charged ions, but provides non-destructive spin-state determination and high resolution motional frequency determination via the continuous Stern-Gerlach effect [1] and image current detection technique, respectively. At the ALPHATRAP experiment, located at the Max-Planck-Institut für Kernphysik (MPIK) in Heidelberg, Germany, we have used exactly this platform to measure the bound electron *g*-factor along the periodic table, with experimental precision better than 1×10^{-10} for both hydrogen-like neon ($Z = 10$) [2] and hydrogen-like tin ($Z = 50$) [3] and we are currently building a next-generation ion source that will allow us to produce and trap few-electron highly charged ions up to hydrogen-like lead ($Z = 98$) or uranium ($Z = 82$) that have binding energies in excess of 100 keV. These high-Z systems allow us to measure higher order QED effects that would be unresolved in lighter systems and let us test the limits of high-precision QED calculations. At low Z however, the *g*-factor of the bound electron can be calculated to the ppt level [4] and below which allows us to use exactly the same experimental procedure to extract related fundamental constants such as the mass of the electron. Using an upgraded experimental apparatus and hydrogen-like $^{12}C^{5+}$ we have recently embarked on a campaign to significantly improve the determination of the electron mass which will directly improve tests of QED in molecular hydrogen ions [5] and can contribute to the determination of the fine structure constant in atom interferometry experiments [6, 7]. I will present the details of this campaign and describe our measurement technique and experimental apparatus, along with an overview of our ongoing efforts to push toward the high-field regime with high-Z HCIs.

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Nonadiabatic relativistic and QED corrections to rovibrational energy levels of the $X^1\Sigma_g^+$ state of hydrogen molecule istopologues

Krzysztof Pachucki [1], **Jacek Komasa** [2, †]

[1]Faculty of Physics, University of Warsaw, ul. Pasteura 5, 02-093 Warszawa, Poland
[2]Faculty of Chemistry, Adam Mickiewicz University, Uniwersytetu Poznańskiego 8, 61-614 Poznań, Poland
†Corresponding author's email: komasa@man.poznan.pl

Recent advancements in spectroscopic techniques have enabled sub-MHz (1 MHz $\approx 3.3 \cdot 10^{-5}$ cm^{-1}) accuracy for selected rovibrational transitions in H_2 and its isotopologues [1–6]. This new level of precision has revealed minor yet significant differences between measurements and theoretical predictions, presenting a new and severe challenge for theoretical models.

To attain similar accuracy in quantum-mechanical computations, it is essential to fully account for interparticle correlation and finite nuclear mass (recoil) effects in the nonrelativistic, relativistic, and quantum-electrodynamic (QED) energy components. In this communication, we report on the results of such calculations, which have been made possible by the recent discovery of new classes of four-particle integrals [7]. Calculations were performed using the direct nonadiabatic (DNA) approach and the four-body nonadiabatic James-Coolidge (naJC) wave function. The naJC wave function includes coupling between the nuclei's rotational angular momentum and the electronic angular momentum. An effective method for reducing the angular dependence of matrix elements facilitated its use in rotationally and vibrationally excited states [8]. Successful incorporation of recoil effects in the principal energy components resulted in reducing the discrepancies between theoretical predictions and experimental findings.

Acknowledgments

This research was supported by the National Science Center (Poland) Grant no. 2021/41/B/ST4/00089. A computer grant from the Poznań Supercomputing and Networking Center was used to perform the numerical calculations.

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Non-adiabatic, relativistic, and QED corrections to the rovibrational intervals of He_2 ($a\ ^3\Sigma_u^+$) and He_2^+ ($X^+\ ^2\Sigma_u^+$)

Ádám Margócsy [1, †], Balázs Rácsai [1], Péter Hollósy [1], Péter Jeszenszki [1], Edit Mátyus [1]

[1]Faculty of Chemistry, Eötvös Loránd University, Pázmány Péter sétány 1/A, 1117 Budapest, Hungary
†corresponding author's email: adam.margocsy@ttk.elte.hu

Spectroscopists have been interested in the low-lying electronically excited states of He_2 (the lowest being $^3\Sigma_u^+$, denoted as a) and their cation (ground state $^2\Sigma_u^+$, denoted as X^+) for decades. These excited states are strongly bound compared to the $^1\Sigma_g^+$ ground state and, therefore, have much richer rovibrational spectra. The accuracy of the experiment has improved drastically over the years for this system [1, 2], the uncertainty of measured rotational intervals or vibrational spacings being on the order of $\sim 10^{-4}$ cm^{-1} or even less. At the same time, theoretical predictions lag behind in many respects. While there are recent computations for the rotational-vibrational levels of the cation [3], only older results are available for He_2 a, which show a non-negligible discrepancy with experiment [4, 5, 6].

I present the joint effort of our group towards the accurate computation of rovibrational and fine-structure levels of He_2 a, and improved computations for He_2^+ X^+. Using an explicitly correlated Gaussian basis representation, we computed variationally the non-relativistic Born-Oppenheimer potential energy curves (PEC). Along each PEC, diagonal Born-Oppenheimer correction and non-adiabatic mass corrections [7] were computed, as well as accurate leading-order relativistic and quantum-electrodynamical (QED) corrections using regularization techniques [8, 9, 10, 11, 12]; higher-order QED corrections and nuclear finite size effects were approximately taken into account. Accurate rotational-vibrational energies were found by solving the Schrödinger equation of the nuclei with the corrected PEC. In the case of He_2 a, the magnetic dipole interaction gives rise to zero-field splitting and the fine-structure splitting of rotational energy levels. This splitting was also obtained by computing the relativistic and QED couplings between the $M_S = -1, 0, +1$ components of the He_2 a state.

Our work improves significantly on previous theoretical results for the rotational intervals, as well as the vibrational spacings.When QED corrections are properly taken into account, the computed fine-structure intervals are in similarly excellent agreement with available experimental data [13, 14].

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The Excited Electronic States of the Helium Dimer Including Relativistic and Adiabatic Effects

Dawid Dąbrowski[1,*], **Marcin Gronowski**[1], **Michał Przybytek**[2], **Michał Tomza**[1,†]

[1]Faculty of Physics, University of Warsaw, ul. Pasteura 5, 02-093 Warszawa, Poland
[2]Faculty of Chemistry, University of Warsaw, ul. Pasteura 1, 02-093 Warszawa, Poland
[*]d.dabrowsk12@student.uw.edu.pl [†]michal.tomza@fuw.edu.pl

Background The helium dimer serves as an exemplary system for advancing our understanding of few-body physics, high-resolution laser spectroscopy, and the properties of ultracold molecules. The electronic structure of four-electron systems, like He_2, can be calculated with unparalleled accuracy. While previous *in silico* studies have attained a reasonable level of accuracy, they remain insufficient for reliably guiding and interpreting state-of-the-art experiments. The last high-accuracy calculation [1] deviates from the experimental results by approximately 1.5‰, which is still inadequate for making direct comparisons and providing meaningful insights for cutting-edge spectroscopic research. Highly accurate *ab initio* results not only allow for a direct comparison with experimental data but also guide upcoming experiments and pave the way towards the verification of the Standard Model.

Purpose This study aims to achieve benchmark-quality potential energy curves (PECs) with the highest possible accuracy for the few lowest excited states of the helium molecule. We systematically explore these states using various methods and basis sets to provide a reliable estimate of the accuracy of our computations. After incorporating relativistic and adiabatic corrections, we achieve an exceptional level of accuracy, which is essential for guiding ongoing experiments.

Method We utilize an extensive range of molecular electronic structure theory methods, including coupled cluster approaches (CCSD(T), CCSDT, EOM-CCSD, EOM-CC3) and configuration interaction (Full CI) methods. Our calculations employ basis sets developed for the He(^{1}S) + He(^{3}S) states with cardinal numbers up to 10Z, with results extrapolated to the complete basis set limit.

Results Potential energy curves (PECs) are calculated for interatomic distances up to 50 a_0. The states from the first four asymptotes are computed using the Full CI method with basis sets up to 7Z and various coupled cluster methods with basis sets up to 8Z. Additionally, a single-point calculation for the $a^3\Sigma_u^+$ and $c^3\Sigma_g^+$ states is provided in the 8Z basis set using Full CI, and in the 10Z basis set using EOM-CC3 to demonstrate convergence at the global minimum. Our calculations achieve a theoretical accuracy reaching **1.0 cm^{-1} (60-200 ppm)** at the minimum.

Conclusions The results of our calculations provide highly accurate data, enabling the calculation of Franck-Condon factors for higher Rydberg states of the helium dimer or the helium molecular ion [2]. We report that our study has achieved the highest accuracy for the helium dimer in excited electronic states.

Acknowledgments

Polish high-performance computing infrastructure PLGrid, grants no. PLG/2023/016878 & PLG/2024/017527.
European Research Council (ERC), grant no. QuantMol/101042989.
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Revisiting proton finite-size corrections in (muonic) hydrogen

Franziska Hagelstein [1,2 †], **Vadim Lensky** [1], **Sotiris Pitelis** [1,2], **Vladyslava Sharkovska** [1,2,3]

[1] Institut für Kernphysik, Johannes Gutenberg-Universität Mainz, D-55128 Mainz, Germany
[2] Paul Scherrer Institut, Forschungsstrasse 111, CH-5232 Villigen PSI, Switzerland
[3] Department of Physics, University of Zurich, CH-8057 Zurich, Switzerland
†corresponding author's email: hagelste@uni-mainz.de

In this talk, I would like to discuss the proton finite-size corrections to the Lamb shift and hyperfine splitting of (muonic) hydrogen. A re-analysis of the $(Z\alpha)^5$ corrections, based on electron-proton scattering data, is presented, discussing limitations of the scattering data and in the finite-size expansion. Furthermore, we point out that the recent lattice-QCD evaluation of the Compton scattering subtraction function [1] needs to include an additional finite-size correction in order to provide a prediction of the total proton two-photon-exchange contribution.

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Hadronic vacuum polarization: contributions to spectra of hydrogen-like atoms and ions revisited

Franziska Hagelstein[1,2], **Vadim Lensky**[2,†], **Bogdan Malaescu**[3], **Vladimir Pascalutsa**[1]

[1]Institut für Kernphysik, Johannes Gutenberg-Universität Mainz, D-55128 Mainz, Germany
[2]Paul Scherrer Insitut, CH-5232 Viligen PSI, Switzerland
[3]LPNHE, Sorbonne Université, Université Paris Cité, CNRS/IN2P3, 75252 Paris, France
†corresponding author's email: vlenskiy@uni-mainz.de

The unprecedented precision reached by experimental measurements of energy spectra of the simplest atomic systems, hydrogen-like atoms and ions (see, e.g., the most recent CODATA report [1] and references therein), demands high-precision theoretical predictions of the corresponding energy levels to test the underlying physics. While QED provides the overwhelmingly dominant (and, as a rule, calculable to a very high precision) part of the theory results [2], the contributions of hadronic and nuclear degrees of freedom often limit the theoretical accuracy. Their importance has recently been made even more prominent thanks to the experimental progress with muonic atoms (see [3] and references therein), where the short distance between the muon and the nucleus increases the sensitivity to dynamics at nuclear and hadronic scales [4, 5].

Here, we reexamine the leading effect of hadronic vacuum polarization on the hyperfine splitting of normal and muonic hydrogen, as well as muonic $^3He^+$ ion. In particular, we investigate the effects of the recoil corrections and of the nuclear electromagnetic form factors on the hadronic vacuum polarization contribution. We find that both of these are very important numerically. We compare our results with previous work [6, 7, 8]. The updated values obtained by us are important, in particular, in view of the experiments envisaged by the CREMA and FAMU collaborations that aim to measure the hyperfine splitting of the $1S$ level in muonic hydrogen and muonic $^3He^+$ [9, 10, 11].

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QED field Hamiltonian decomposition

Michael I. Eides

Department of Physics and Astronomy, University of Kentucky, Lexington, KY 40506-0055 USA
corresponding author's email: meides@g.uky.edu

Decomposition of the field Hamiltonian for a loosely bound QED state is considered. It is demonstrated in the one-loop approximation that the so called quantum anomalous energy has wrong parametric dependence and therefore should not be included as a separate term in the QED field Hamiltonian [1].

Acknowledgments

This work was supported by the NSF grant No. PHY- 2011161.

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WEDNESDAY

May 28th, 2025

Microwave spectroscopy of positronium: progress and future prospects

D. B. Cassidy

Department of Physics and Astronomy, University College London, Gower Street, London, WC1E 6BT, United Kingdom

The leptonic positronium (Ps) atom is a well-established system with which to test QED theory and fundamental symmetries, and may even be used to test for new physics [1]. Such tests may be performed via spectroscopic means or by looking at various annihilation decay modes, some of which are forbidden by various discrete symmetries, such as charge conjugation, parity and spatial transformations (i.e., C, P and T) and combinations thereof, [2]. For many years the experimental precision of optical and microwave spectroscopic measurements of Ps energy levels has been much lower than the corresponding QED calculations, generally by an order of magnitude or more [1]. Recent work at UCL has been undertaken to address this imbalance by performing improved microwave spectroscopy of the PS n = 2 fine structure [3]. Some advances have been made, which in turn have revealed some systematic effects that must be addressed before more progress can be made. In this talk I will give a summary of these measurements, and discuss how we plan to move forward tpo higher precision tests. I will also discuss some related work using Ps microwave methods, such as testing C symmetry [4] and measurements the spin polarization of a slow positron beam [5].

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Current status of precise measurement of muonium hyperfine structure in high magnetic field at J-PARC MUSE

Y. Goto [A], M. Abe [B], K. Fukui [A], S. Fukumura [C], M. Fushihara [A], T. Hishinuma [C], S. Kanda [B,D], M. Kitaguchi [A,E], S. Nishimura [B], T. Okudaira [A,F], A. Powell [G], K. Sasaki [B], H. M. Shimizu [A], K. Shimomura [B,D], P. Strasser [B,D], H. Tada [A], H. A. Torii [H], T. Yamanaka [I], T. Yamazaki [B], MuSEUM collaboration

[A] Graduate School of Science, Nagoya University, Japan
[B] High Energy Accelerator Research Organization (KEK), Japan
[C] Graduate School of Science and Technology, Niigata University, Japan
[D] The Graduate University for Advanced Studies, Japan
[E] Kobayashi-Maskawa Institute, Nagoya University, Japan
[F] Advanced Science Research Center, Japan Atomic Energy Agency (JAEA), Japan
[G] CERN, Switzerland
[H] School of Science, The University of Tokyo, Japan
[I] Faculty of Arts and Science, Kyushu University, Japan
[†] corresponding author's email: [ygoto@phi.phys.nagoya-u.ac.jp]

Muonium is a pure leptonic binary system consisting of a positive muon and an electron, and its level structure can be calculated with high precision. The Muonium Spectroscopy Experiment Using Microwave (MuSEUM) experiment aims to verify the quantum electromagnetic dynamics theory and determine the positive muon magnetic moment and mass by precise measurements of the ground-state hyperfine structure of muonium. There are two methods to measure the hyperfine structure of muonium: Spectroscopy of the energy level differences at zero magnetic field and those between Zeeman splitting sublevels in high magnetic field. Hyperfine structure of muonium can be determined in both methods and the muon-proton magnetic moment ratio can be determined from the two transition frequencies between two pairs of sublevels measured in high magnetic field and the proton NMR frequency, which is proportional to the magnetic field. The most precise value of the hyperfine structure of muonium was determined from high field experiment at LAMPF, an accelerator facility in Los Alamos, in 1999 [1]. We aim to improve the precision of the hyperfine structure of muonium by an order of magnitude using the high-intensity pulsed muon beam at Japan Proton Accelerator Research Complex (J-PARC) in 1 MW operation. The zero field experiment at J-PARC MLF MUSE D-Line was completed with a precision of 160 ppb in 2017 [2, 3], and the first high field measurement under 100 kW operation was performed at MUSE H-Line, the new high intensity beamline, from February to March this year. We plan to conduct long-time measurements aiming at updating the precision of the previous study with more reduced systematic uncertainty by precisely controlling the magnetic field, temperature, and so on from November of this year. This talk will report on the current state of preparation including the latest results.

Acknowledgments

This research was supported by the Japanese JSPS KAKENHI Grant No.JP20H05646, JP21H04463, JP23K22503. Muon experiment at the Materials and Life Science Experimental Facility of J-PARC was performed under a user program (Proposals No. 2017A0134, 2017B0224, 2018A0071, 2018B0314, 2019A0144, 2020B004).

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New results of positronium 1S-2S transition and Muonium Fine structure

Edward Thorpe-Woods [1†] on behalf of the Mu-MASS collaboration and the Exotic Matter group at ETH Zurich

[1]Institute for Particle Physics and Astrophysics, ETH Zurich, Otto-Stern-Weg 5, 8049 Zurich (Switzerland)
†corresponding author's email: ethorpe@ethz.ch

Positronium and muonium, as purely leptonic atoms without internal structure, provide ideal systems for high-precision tests of quantum electrodynamics (QED) [1] and measurements of fundamental constants. Here, we present our recent results of the $1^3S_1 \rightarrow 2^3S_1$ transition in positronium, measured via two-photon optical spectroscopy with a continuous-wave laser. The preliminary analysis estimates that the total uncertainty of this measurement at 5 ppb, comparable to the most precise measurement to date (2.6 ppb) [2]. We also present a semi-analytical model for the lineshape of 1S-2S transitions in positronium. This expands on previous work with stable atoms [3, 4], and demonstrates remarkable agreement with lineshapes generated via Monte-Carlo simulations and validated by experimental data. This model provides a tool for optimising experimental parameters and for gaining deeper insights without the need for computationally intensive simulations. The future prospects of positronium and muonium 1S-2S spectroscopy employing a novel Ramsey-Doppler scheme [5] will also be presented.

In addition, we present a recent measurement of the fine structure of muonium, which follows from the experiment that determined the muonium Lamb shift [6, 7]. A preliminary analysis of the experimental data indicates that the observed transition frequency is consistent with theoretical predictions, with a total uncertainty of around about 7 parts in 10,000, making it the most precise determination to date. The upcoming High-Intensity Muon Beam (HiMB) at the Paul Scherrer Institute (PSI) in Switzerland will allow to increase the statistics on such a measurement to enable precise tests of bound state QED, while also providing tests of new physics [8].

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LEMING - towards muonium interferometry

Anna Sótér [1, *], Robert Waddy [1, †], and the LEMING collaboration

[1]Institute for Particle and Astrophysics, ETH Zürich, 8093, Zürich, Switzerland
[*] Email: asoter@phys.ethz.ch
[†] Speaker, email: rwaddy@ethz.ch

The LEMING experiment aims to measure the gravitational free fall of muonium (Mu = $\mu^+ + e^-$), a purely leptonic, exotic atom. The experiment will be a unique probe to test the weak equivalence principle on elementary, second-generation antimatter using a system without large contributions to the mass from the strong interaction.

This talk will discuss the feasibility of making such a measurement to an error of approximately 1%. The experiment will employ atom interferometry using a three-grating interferometer, which relies on a novel, cold vacuum muonium source with a narrow energy and transverse momentum distribution. We have demonstrated the working principle of such a novel source based on muonium conversion of conventional muon beams in a thin layer of superfluid helium, which provided approximately 8% conversion efficiency to an atomic beam with 25 mrad angular divergence. Besides having the potential to improve the precision of Mu 1S-2S spectroscopy, this beam paves the way towards Mu interferometry.

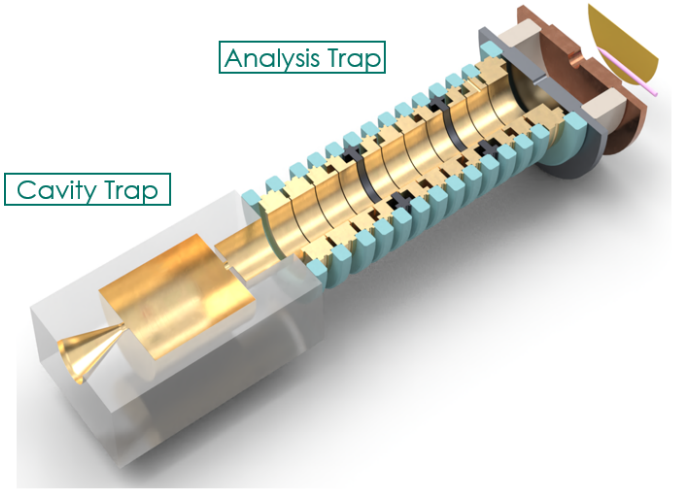
A far-field, aperture near-field interferometer, based on the Talbot pattern, is being designed for this purpose, where the vertical phase of the interferogram encodes the gravitational acceleration of the atoms, which will be sampled by scanning the third (masking) grating. The main challenges include strict control over vibrational, displacement, and alignment constraints of a sub-nanometer measurement, while allowing for simultaneous X-ray calibration measurement.

The Lepton SYMmetry experiment

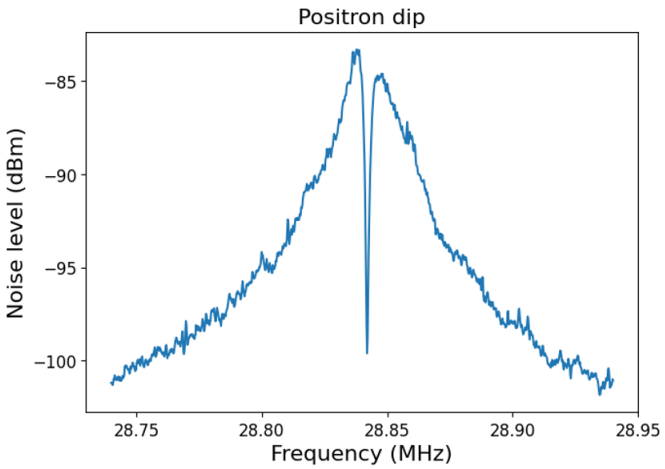
Maria Pasinetti [1, †], **Fabian Raab** [1], **Paul Holzenkamp** [1], **Andreas Thoma** [1], **Luca Falzoni** [1], **Sangeetha Sasidharan** [1], **Sven Sturm**[1]

[1]Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, D-69117 Heidelberg

LSym is a new cryogenic Penning trap experiment currently being designed at the Max-Planck-Institut für Kernphysik of Heidelberg. The goal of Lsym is to conduct a stringent CPT test by comparing the properties of matter and antimatter with unprecedented precision. To this end, we simultaneously trap one electron and one positron in a Penning trap and perform a decoherence-free comparison of their spin precession frequencies [1]. Currently, we are developing and testing techniques to capture positrons inside the cryogenic vacuum. This involves moderating positrons from a rather weak ^{22}Na β^+ source and producing positronium atoms in a high Rydberg state. These atoms are subsequently ionized in the Penning trap, where the positron is retained [2]. Finally, the positron will be cooled to the ground state of motion and can be detected with an image current detector. This poster illustrates the principles and techniques that will be used for the positron source at Lsym.



(a) Our trap stack at LSym, currently in the design phase.



(b) Our first positron dip in the LSym lab.

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Searching for electric dipole moments using a compact frozen-spin trap

Chavdar Dutsov [1,*], **Timothy Hume** [1,2,†], **Philipp Schmidt-Wellenburg** [1]

(on behalf of the muEDM Collaboration)

[1]PSI Center for Neutron and Muon Sciences, 5232 Villigen PSI, Switzerland
[2]ETH Zürich, 8093 Zürich, Switzerland
[†] timothy.hume@psi.ch
[*] Present address: CERN Accelerator Systems Department, 1211 Meyrin, Switzerland

The frozen-spin technique [1] will enable a direct measurement of the muon electric dipole moment (EDM) with unprecedented sensitivity. The muEDM Collaboration is developing a compact frozen-spin trap to demonstrate this technique for the first time [2]. Using the high intensity continuous muon source at the Paul Scherrer Institute, a target sensitivity of 6×10^{-23} $e$cm could be realised, exceeding the current limit [3] by a factor of 1000 and thus extending our reach towards new physics involving CP violation. To implement the frozen-spin technique, 28 MeV/c muons will be injected off-axis into a 3 T superconducting solenoid and stored at its centre with an orbital radius of approximately 30 mm. A pulsed radial magnetic field will be used to kick the axial momentum as it enters the storage region such that it can be axially confined within a static weakly-focusing field. A radial electric field can be tuned such that the spin precession induced by the anomalous magnetic moment can be suppressed, thus permitting only spin precession out of the orbital plane. Scintillating fibres will be used for positron tracking to search for a corresponding change in the emission asymmetry over time. With systematic effects controlled [4], this would be the experimental signature for a nonzero EDM. This technique is also applicable to beta-radioactive ions [5], for which EDM measurements of light nuclei could offer complementary sensitivity to nucleon EDMs and additional sources of CP violation. This talk will detail the implementation of the frozen-spin technique and outline the key milestones for our Collaboration. In particular, the demanding requirements for the kicker magnet and pulsed power supply to achieve the pulsed magnetic field will be presented, along with the status of their development.

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Precision measurement of the radii of light nuclei with high-resolution x-ray spectroscopy

Ben Ohayon, for the QUARTET collaboration

Physics Department, Technion – Israel Institute of Technology, Haifa 3200003, Israel
bohayon@technion.ac.il

Our knowledge of the nuclear charge radius is often the limitation to the precision with which we can confront theory with experiment. Such comparisons allow us to determine the fundamental constants [1] and search for new physics [2]. The most accurate charge radius determinations are through its effect on the energy levels of muonic atoms—compact exotic bound systems where a negative muon orbits a nucleus. Although the radii of nearly 300 nuclei have been measured in this way, those of light nuclei that extend from lithium to neon are poorly known [3].

The QUARTET experiment aims to improve the radii of light nuclei by an order of magnitude [3]. To do so we employ a novel quantum sensing technology for photon energies—metallic magnetic calorimeters [4]. In October 2024, we have taken data with enriched targets of ^{6}Li, ^{7}Li, ^{9}Be, ^{10}B and ^{11}B with enough statistical accuracy to significantly improve their radii. In this talk I will show preliminary results from the ongoing analysis and discuss the interplay with other precision measurements such as the laser spectroscopy of helium-like ions.

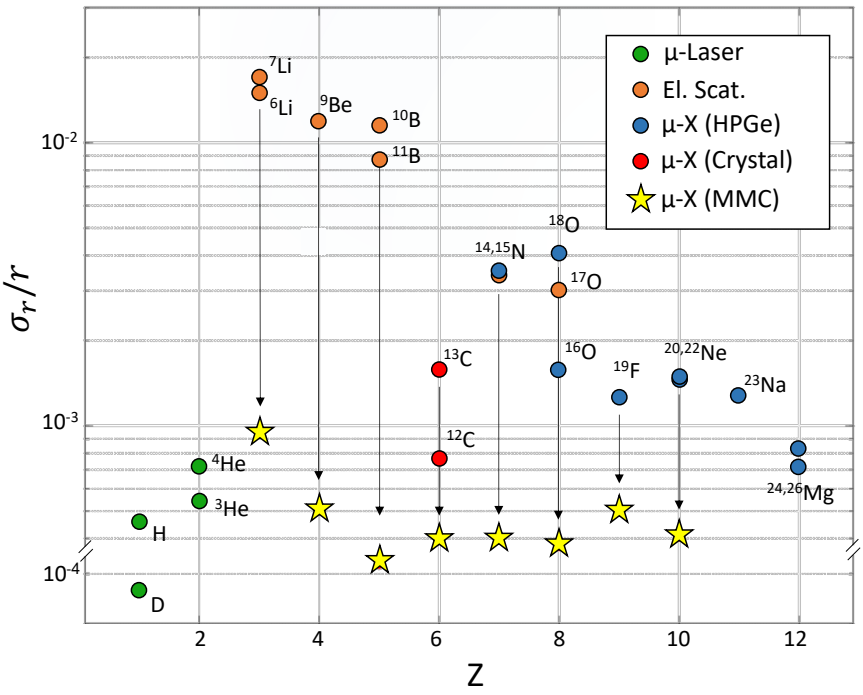

Figure 1: Current status [5, 6] and our accuracy goals for the radii of light nuclei

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Precision Spectroscopy of Antiprotonic Atoms for Probing Strong-Field QED

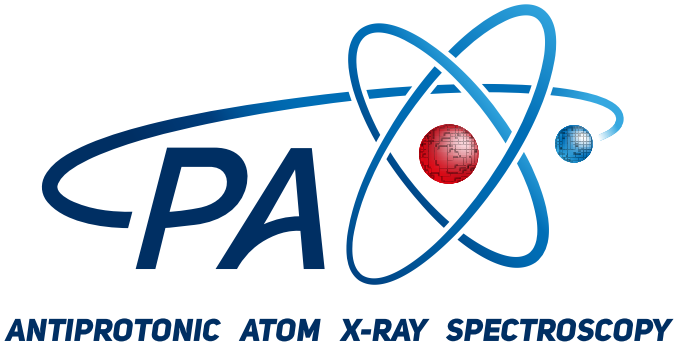
Shikha Rathi[1,2], **for the PAX collaboration**

[1]Physics Department, Technion – Israel Institute of Technology, Haifa 3200003, Israel
[2]Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS-PSL Research University, Collège de France, Case 74; 4, place Jussieu, F-75005 Paris, France
shikha.rathi@lkb.upmc.fr

Precision measurements in quantum systems are critical for testing the boundaries of the Standard Model and exploring new physics [1]. Such investigations depend on a precise understanding of quantum electrodynamics (QED), one of the fundamentally best-understood theories. While bound-state QED (BSQED) predictions have been validated to high precision (parts per 10^{12}) in simple systems like hydrogen [2], its predictions for high-Z atoms in strong Coulomb fields remain largely untested beyond first-order interactions. This limitation arises from experimental challenges and fundamental theoretical uncertainties related to nuclear effects [3].

PAX is a new experiment designed to test strong-field BSQED up to second-order through x-ray spectroscopy of antiprotonic atoms. These exotic systems exhibit Coulomb fields two to seven orders of magnitude stronger than those in their highly charged ion counterparts, amplifying QED effects and making them more accessible to measurement [4]. Our aim is to measure Rydberg transitions in gaseous targets using a novel Transition Edge Sensor x-ray detector, enabling high-precision measurements with a large solid angle and intrinsic resolution of ∼50 eV (FWHM) in the 50–250 keV range, achieving an accuracy of 10^{-5}–10^{-6}. The PAX strategy will effectively eliminate uncertainties from the nucleus, allowing direct and purely QED-focused measurements.

First prototype detector tests for PAX are being conducted in the TELMAX zone at ELENA, CERN. I will present the current status of the test beam, and prospects for the next phases of the experiment.



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Probing New Physics with Exotic Atoms

Hongkai Liu, [1,2]**, Ben Ohayon** [1]**, Omer Shtaif** [1, †]**, Yotam Soreq** [1]

[1]Physics Department, Technion – Israel Institute of Technology, Haifa 3200003, Israel
[2]High Energy Theory Group, Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA
†omer.shtaif@campus.technion.ac.il

High-precision atomic spectroscopy is a significant tool for determining fundamental constants, e.g., [1] as well as searching for new particles beyond the standard model (SM) e.g., [2]. New particles can be manifested as deviations from the SM prediction for transition energies and can be identified by meticulously comparing theory and experiment. In particular, heavy-nuclei exotic atoms in circular states offer a twofold advantage in a new particle search. First, as their reduced masses are larger than electronic atoms, the average distance between their constituents is smaller, resulting in sensitivity to particle masses $O\left(10^3\right)$ heavier. Second, their high angular momentum considerably suppresses contributions from the strong nuclear force and finite-size corrections, allowing the SM prediction to be calculated to a sub-ppm precision [3], above the estimated precision of upcoming experiments.

In this talk, I will present the results of a new physics search in such atomic systems including world-leading bounds for several benchmark models and near-future projections. I will distinguish between two scenarios. If the nuclei are not too heavy, bounds can be set directly by comparing the experimental and theoretical transition energies. On the other hand, heavy-nuclei atoms have a relevant nuclear polarizability contribution, which is poorly determined at present time [4]. Nevertheless, I will show that utilizing two energy transitions enables a novel probe of new physics and nuclear polarizabilities simultaneously, with minimal loss in sensitivity.

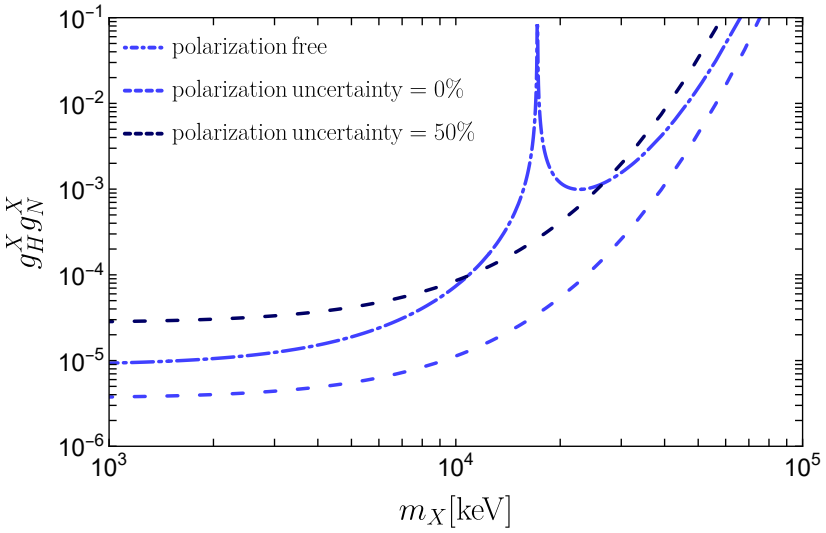

Figure 1: Projections of the $\bar{p}^{132}$Xe sensitivity to new particles. The dual-transition method removes the nuclear polarizability uncertainty with minimal loss in sensitivity.

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Toward High-Precision XUV Spectroscopy of the 1S-2S Transition in He^+

Florian Egli [1, †], **Jorge Moreno** [1], **Johannes Weitenberg** [1,2], **Theodor W. Hänsch** [1,3], **Thomas Udem** [1,3], **Akira Ozawa** [1,4]

[1]Max-Planck-Insititut für Quanten Optik, Hans-Kopfermann-Straße 1, 85748 Garching, Germany
[2]Fraunhofer-Institut für Lasertechnik ILT, Steinbachstraße 15, 52074 Aachen, Germany
[3]Fakultät für Physik, Ludwig-Maximilians-Universität München, Schellingstraße 4, 80799 Munich, Germany
[4]Institute for Multidisciplinary Sciences, Yokohama National Univeristy, 79-5 Tokiwadai, Hodogaya Ward, Yokohama City, 240-8501 Kanagawa, Japan
†corresponding author's email: florian.egli@mpq.mpg.de

Bound-state quantum electrodynamics (QED) accurately describes the energy levels of hydrogen-like atoms and ions. High-precision laser spectroscopy experiments provide one of the best tests of the theory. The frequency of the narrow 1S-2S transition of atomic hydrogen has been measured with a relative uncertainty of less than 10^{-14}. By combining two spectroscopic measurements of a hydrogen-like system, the Rydberg constant and the nuclear charge radius can be determined. The comparison of physical constants obtained from different measurement combinations serves as a consistency check for the theory [1]. It is valuable to study different hydrogen-like systems, as they exhibit varying sensitivities to different contributions of the theory. The measurement of the Lamb shift in muonic hydrogen, for instance, has enhanced sensitivity to the proton radius and led to the proton radius puzzle [2].

Another interesting spectroscopic target is the hydrogen-like He^+ ion. Higher-order QED corrections scale with high powers of the nuclear charge, making He^+ significantly more sensitive to these effects than hydrogen. We are preparing an experiment to measure the 1S-2S two-photon transition in He^+ [3]. Ideal conditions for high-precision measurements are achieved by holding a small number of He^+ ions nearly motionless in the field-free environment of a Paul trap, where they are sympathetically cooled by co-trapped Be^+ ions. The 1S-2S transition will be excited by an extreme-ultraviolet (XUV) frequency comb at 60.8 nm, generated via high-harmonic generation from a high-power infrared frequency comb. After successful excitation to the 2S state, a significant fraction of the He^+ ions will be further ionized to He^{2+} and remain in the Paul trap. Sensitive in-situ mass spectrometry using secular excitation will detect the number of trapped He^{2+} ions, serving as a single-event-sensitive spectroscopy signal.

To perform Doppler-free spectroscopy of the He^+ transition, two counterpropagating pulses of the frequency comb must overlap spatially and temporally at the ion position. Achieving this overlap before the spectroscopy experiment is crucial to find the spectroscopy signal within a reasonable measurement time, making it a critical preparatory milestone. Another key milestone is the installation of a custom XUV spectrometer to fine-tune the spectral envelope of the frequency comb to match the expected He^+ transition.

This poster provides an update on the progress toward He^+ spectroscopy in our experiment and offers an opportunity to further discuss the details presented in the accompanying talk.

Acknowledgments

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (Grant Agreement No. 742247). T. W. Hänsch acknowledges support from the Max-Planck Foundation.

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High-Precision Penning-Trap Mass Spectrometry of Actinides at TRIGA-Trap

Tanvir Sayed [1], Szilard Nagy [1, †], Klaus Blaum [1], Michael Block [2,3,4], Burcu Cakirli [1], Stanislav Chenmarev [1], Christoph Düllmann [2,3,4], Dennis Renisch [2,3]

[1]Max-Planck-Institut für Kernphysik, 69117 Heidelberg, Germany
[2]Helmholtz-Institut Mainz, 55128 Mainz, Germany
[3]Department Chemie - Standort TRIGA, Johannes Gutenberg-Universität Mainz, 55128 Mainz, Germany
[4]GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany
†corresponding author's email: szilard.nagy@mpi-hd.mpg.de

Penning traps are widely used in high-precision mass spectrometry to determine atomic masses with exceptional precision and accuracy, playing a crucial role in atomic and nuclear physics research [1]. TRIGA-Trap is a high-precision, double penning-trap mass spectrometer located in the reactor hall of the TRIGA (Training, Research, Isotopes, General Atomic) research reactor in Mainz, Germany [2]. It also serves as one of the development platforms for the planned MATS (Measurements of very short-lived nuclides using an Advanced Trapping System) experiment at FAIR (Facility for Antiproton and Ion Research) which aims to investigate nuclei far from stability in order to enhance our knowledge on their fundamental nuclear properties and interactions [3, 4]. While the construction of FAIR is still underway, development platforms such as TRIGA-Trap conduct studies to optimise future experiments and test new emerging ideas.

At TRIGA-Trap, mass measurements of radioactive nuclides – particularly actinides – are performed with the PI-ICR (Phase-Imaging Ion-Cyclotron Resonance) technique. This method offers high sensitivity, resolving power and accuracy, while requiring relatively short measurement times [2]. Recent mass measurements of actinides, including ^{244}Pu, ^{241}Am, ^{243}Am, ^{248}Cm, and ^{249}Cf have achieved uncertainties at the parts-per-billion (ppb) level [5]. Currently, mass measurements in the Pu isotopic chain – including ^{238}Pu, ^{239}Pu, ^{240}Pu, and ^{242}Pu – are planned and in progress. These nuclides are in the vicinity of the neutron number $N = 152$, a region associated with a deformed sub-shell closure. The precise mass measurements allow the exploration of nuclear structure through trends in mass filters, such as S_{2n} (two-neutron separation energies) and $\delta V_{p,n}$ (average p-n interaction of the most loosely-bound two nucleons), as well as their differentials [5].

This presentation will provide an overview of the current status of the experiment, including recent mass measurements, their application in nuclear structure evaluation, and the investigations into systematic uncertainties that contribute to accurate mass determinations.

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New bounds on the Standard Model Extension coefficients in the proton sector from Rabi-type hyperfine spectroscopy of deuterium

Amit Nanda[1,2,†], **D. Comparat**[3], **O. Dulieu**[3], **S. Lahs**[3], **C. Malbrunot**[4,5,6], **L. Nowak**[1,2], **Martin Simon** [1], **and E. Widmann** [1]

[1]*Stefan Meyer Institute, Austrian Academy of Sciences, Dominikanerbasteri 16, 1010, Vienna, Austria*
[2]*Vienna Doctoral School in Physics, University of Vienna, Universitätsring 1, 1010, Vienna, Austria*
[3]*Université Paris-Saclay, CNRS, Laboratoire Aimé Cotton, 91405, Orsay, France*
[4]*TRIUMF, 4004 Wesbrook Mall, Vancouver, BC V6T 2A3, Canada*
[5]*Physics Department, McGill University, Montréal, Québec H3A 2T8, Canada*
[6]*Department of Physics and Astronomy, University of British Columbia, Vancouver BC, V6T 1Z1, Canada*
†*corresponding author's email:* amit.nanda@oeaw.ac.at

The Standard Model (SM) and General Relativity (GR) form the cornerstone of modern physics, describing fundamental particles and interactions. Bridging the gap between these frameworks still remains a key challenge, particularly due to gravity's exclusion from the SM and the incompatibility of quantum mechanics with GR. There have been many effective field theory approaches, which try to address this gap. However, the Planck scale suppression makes observable experimental signatures originating from such theories extremely tough to deal with. The Standard Model Extension (SME) [1] framework emerges as a pivotal effective field theory that integrates SM and GR while permitting Lorentz and CPT symmetry violations [1, 2, 3] and providing a basis for experimental and theoretical investigations of these fundamental symmetry violations. In its initial stages, the Lorentz violating operators in SME were restricted to mass dimensions $d \leq 4$ and was popularly known as the minimal SME. Later on, operators of arbitrary mass dimensions were also included in the so called non-minimal SME, opening the path for additional searches of Lorentz violation [4].

The Lorentz violating perturbations contribute to energy shifts in atomic spectra at the leading order of momentum of the electron or the nucleons [5, 6]. The sensitivity of the SME coefficients controlling the amount of Lorentz violation is proportional to $\delta\nu_{\rm exp}/\langle|p_w|^k\rangle$, where $\delta\nu_{\rm exp}$ is the experimental limit on the frequency shift in an atomic spectrum and p_w is the momentum of the particle of flavor $w \in \{\mathrm{e}, \mathrm{p}, \mathrm{n}\}$. The relative momentum of the proton in the deuterium nucleus is about 5 orders of magnitude higher than the momentum of the proton in hydrogen. Based on theoretical estimates [7], a 10 Hz limit on the $\delta\nu_{\rm exp}$ in deuterium would surpass the sensitivity of the proton coefficients in the non-minimal SME as compared to that of 0.1 mHz limit in hydrogen [8] by 5 orders of magnitude for $k = 2$ and by 15 orders of magnitude for $k = 4$.

In the pursuit of Lorentz violating signals, we performed the hyperfine spectroscopy measurements in deuterium focusing on any observation of the sidereal variations [5, 6, 7] of the measured transition frequencies. This talk will provide an overview of the in-beam Rabi type experimental setup that we used for the measurements, with a focus on the lumped mode microwave structure [9, 10] inspired Doubly split ring resonator (DSRR) used as a spectrometer. The talk will report on the constraints on the spherical coefficients for Lorentz violation in the proton sector in non-minimal SME obtained via measurement of the σ transitions in deuterium ($F = 3/2 \rightarrow F = 1/2,\ \Delta m_F = 0$). The constraints on the spin-dependent SME coefficients for proton have been improved by 5 and 15 orders of magnitude for $k = 2$ and, $k = 4$ respectively. For the first time, bounds have been placed on the spin-independent proton SME coefficients for $k = 2$ and $k = 4$

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THz Spectroscopy of Rydberg Positronium

Rebecca J. Daly [1, †], **David B. Cassidy** [1]

[1]Department of Physics and Astronomy, University College London, Gower Street, London, WC1E 6BT, United Kingdom
†corresponding author's email: rebecca.daly.18@ucl.ac.uk

Positronium (Ps) is purely leptonic, making its spectroscopy ideal for tests of bound-state QED theory. Specifically, spectroscopy of Ps in Rydberg states can be used to obtain a measurement of the Rydberg constant. Here, we present the results of spectroscopy performed in the THz regime between Rydberg states of Ps. Using a trap-based pulsed positron beam, we produce ground-state Ps atoms and subsequently optically excite them to a range of Rydberg states. Using a quadrupole guide, the Rydberg Ps atoms are guided around a 45-degree bend, and away from the guiding magnetic fields along the positron beam-line. At the end of the quadrupole guide, a THz multiplier is used to drive transitions between different Rydberg states, and the population transfer is measured by selective field-ionization of the states involved.

Collinear Laser Spectroscopy of Helium-like $^{12-14}C^{4+}$

Emily Burbach [1, †], Kristian König [1], Phillip Imgram [2], Patrick Müller [3], Wilfried Nörtershäuser [1], Julien Spahn [1]

[1]Institut für Kernphysik, Technische Universität Darmstadt, Germany
[2]Instituut voor Kern- en Stralingsfysica, Katholieke Universiteit Leuven, Belgium
[3]Physics & Astronomy Department, University of California, USA
†corresponding author's email: eburbach@ikp.tu-darmstadt.de

Light helium-like systems are ideal test cases for nuclear and atomic structure calculations as they exhibit a greatly varying nuclear structure and are accessible for high-precision ab-initio calculations. In an ongoing effort, it is planned to determine absolute and differential nuclear charge radii, R_C and $\delta\langle r^2\rangle$, of the light elements Be to N by purely using collinear laser spectroscopy and non-relativistic quantum electrodynamics calculations in the helium-like ions. As a first step, the $1s2s\,^3S_1 \rightarrow 1s2s\,^3P_J$ transitions in $^{12-14}C^{4+}$ were determined using the Collinear Apparatus for Laser Spectroscopy and Applied Science (COALA) at the Technical University of Darmstadt. Absolute and relative nuclear charge radii were extracted and compared to other experimental and theoretical results. In those measurements a significant splitting isotope shift (SIS) was observed. It is compared to the theoretical SIS, which is determined by the relativistic finite nuclear mass and recoil contributions to the energy [1], which provides a clear test of the experimental accuracy.

Acknowledgments

This project is supported by DFG (Project-ID 279384907 - SFB 1245).

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THURSDAY

May 29th, 2025

Prospects of Higgs Boson Research at the LHC

André Sopczak[1, †]

[1]Institute of Experimental and Applied Physics, Czech Technical University in Prague, Husova 240/5, CZ-11000 Prague 1
†corresponding author's email: andre.sopczak@cern.ch

The search for Higgs bosons in the Standard Model (SM) of particle physics and Beyond the Standard Model (BSM) started intensively at the Large-Electron-Positron (LEP) collider, which operated from 1989 to 2000, and later at the Tevatron from 2001 to 2011. With the discovery of a Higgs boson at the Large Hadron Collider (LHC) at CERN, a new era began. This let to precision measurements of the Higgs boson properties which, so far, are all consistent with the SM expectations. Many searches for predicted BSM Higgs bosons advanced the field of experimental Higgs boson physics. The LHC operated already in three running periods: Run-1 from 2010 to 2012, Run-2 from 2015 to 2018, and currently Run-3 from 2022-2026. The High Luminosity LHC (HL-LHC) operation is foreseen from 2029. The prospects of experimental Higgs boson research for the next decade are reviewed.

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Measurement of the mass of the W boson

Dezső Horváth [1,2, †],

[1]Dept. of Particle Physics, HUN-REN Wigner Physics Research Centre, 29-33 Konkoly-Thege, 1121 Budapest, Hungary
[2]STAR Institute, University Babeș–Bolyai, Strada Mihail Kogălniceanu 1, Cluj-Napoca 400347, Romania
†horvath.dezso@wigner.hu

The mass of the W boson is one of the most important physical constants as it determines the strength and finite range of the charged weak interaction (like the beta decay). It is introduced by the Brout-Englert-Higgs mechanism of spontaneous symmetry breaking in the Standard Model and can be calculated at high precision. It was measured before 2013 by the two Tevatron and four LEP experiments and those results agreed very well with each other and the calculations. Using these measurements the W mass was determined to be 80387 ± 15 MeV, which was accepted as a world average [1]. However, 12 years after the stop of the Tevatron collider, in 2022 the CDF experiment published a new result [2] of high precision (see Fig. 1), which deviated from the previous ones quite significantly: 80433.5 ± 9.4 MeV.

This discrepancy excited the LHC experiments. It is very hard to estimate the W mass at hadron colliders. Because of an overwhelming hadron production background one has to rely on leptonic decays, where the escaping neutrino causes missing energy in the detected events. Two LHC collaborations, ATLAS and LHCb in 2022-23 checked proton-proton collision data from the beginning of the LHC runs when the rate of the simultaneous collisions was not yet that high as later, and have found W masses similar to the world average, although with higher uncertainties. In my talk I shall describe a new CMS measurement [3] of the W mass relying on the muonic decays of W bosons produced in proton-proton collisions at 13 TeV. We have obtained a W mass of 80360.2 ± 9.9 MeV, which has a very high precision, agrees with the world average, and contradicts the 2022 CDF result.

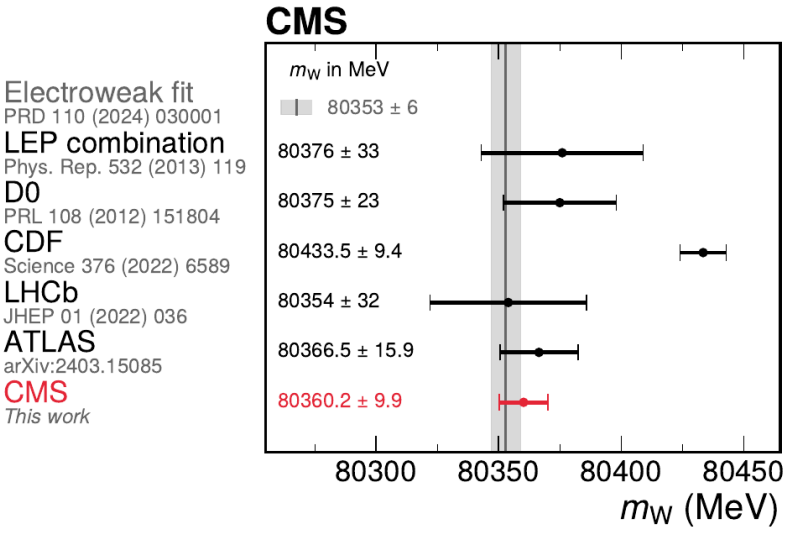

Figure 1: Measurements of the W mass as compared to the Standard Modell calculation (EW fit) shown as a shaded area. Note that the 2013 CDF measurement, which agreed with the D0 one, is not plotted as that was averaged in the new CDF result.

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Effective Field Theory fits of the electroweak sector CMS data

CMS Collaboration

The contribution will report on recent results on global EFT fits of the CMS data, with particular focus on a dimension-6 SMEFT interpretation of the measurements performed in the electroweak sector of the Standard Model, including results built upon likelihoods constructed from reconstructed-level information and properly including all correlations among the various input channels.

The kelvin in the "new SI" - differences between thermodynamic- and ITS-90 temperature - a pathway to improvements in metrology and beyond

Christof Gaiser [1, †], **and Bernd Fellmuth** [1],

[1]Physikalisch-Technische Bundesanstalt (PTB), Abbestrasse 2-12, 10587 Berlin, Germany
†corresponding author's email: christof.gaiser@ptb.de

Since the establishment of the International System of Units (SI), extraordinary advances have been made in linking SI units to invariant quantities such as fundamental constants of physics and properties of atoms. Since 2019, the definition of the kelvin is based on a fixed numerical value of the Boltzmann constant k. The effect of the new definition of the kelvin is that one kelvin is equal to the change of thermodynamic temperature T resulting in a change of thermal energy kT by 1.380649 x 10^{-23} J. It implies the equivalence of mechanical and thermal energy. Thus, k is simply the conversion factor between energy and temperature.

Since 2019, the Mise en pratique for the definition of the kelvin (MeP-K) [1] allows for both the realization and dissemination of thermodynamic temperature T as well as its approximation (T_{90}), the temperature according to the International Temperature Scale of 1990, ITS 90. An improved knowledge of the differences (T-T_{90}) is therefore of eminent importance. In 2011, a working group of the Consultative Committee for Thermometry published their best estimates of (T-T_{90}). Since 2011, the work on the determination of the Boltzmann-constant [2] has stimulated significant improvements in primary thermometry. A recent paper [3] updates the (T-T_{90}) estimates by combining and analyzing the data used for the 2011 estimates and data from more recent primary thermometry. The new data has been obtained by four types of gas thermometry: acoustic, dielectric constant, refractive index, and constant volume. Their uncertainty estimates are now comparable with the uncertainties in the best measurements of thermodynamic temperature values and the uncertainties in ITS 90 realizations.

For users without primary thermometry capability, it is now possible to access thermodynamic temperature values T below 335 K with comparably small uncertainties via an ITS 90 calibration and the transfer applying (T-T_{90}). This is a way to bridge the existing gap between enormous effort for T measurements and comparably good access to T_{90}. The applications in this field are divers and increase with demands for decreasing uncertainties. An example in metrology is the prospering field of alternative pressure standards with T as one of the key parameters. The idea, first expressed in [4], is now tested on a level of 2 ppm [5] at the triple-point-of-water temperature T_{TPW}. This is only possible if T is known on the 1 ppm level which is comparably easy to achieve at T_{TPW}. However, pressure standards are usually operated at room temperature. For such applications, the existing difference (T-T_{90}) of order 3 mK must be known with very small uncertainties. Another example is the field of thermophysical properties where ab initio calculations of gas properties have made enormous progress. To check the theory by experiment, highly accurate measurements are needed. But theory evidently is based on T, whereas the experiments are made with thermometers carrying T_{90}. In the future, it is very likely that the group of users will increase, and with new measurements in the temperature range above 335 K, the range of low uncertainty (T-T_{90}) estimates will be extended.

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The Measurements of the Newtonian Constant of Gravitation - A Short Overview

Christian Rothleitner [1, †], **Stephan Schlamminger** [2]

[1]Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, 38116 Braunschweig, Germany
[2]National Institute of Standards and Technology, 100 Bureau Drive, Gaitherburg, MD 20899, USA
†corresponding author's email: christian.rothleitner@ptb.de

Newton's gravitational constant, G, is the measure of the coupling strength of gravity, the weakest of the four fundamental interactions known to men. Henry Cavendish carried out the first laboratory measurement of that interaction strength in 1798 using a torsion balance. In the next 227 years, many more measurements of the gravitational constant were carried out. In some periods, there was lots of activity. In other time periods, it was relatively quiet with only one or a few measurements.

The last forty years have been a time where many measurements of G were carried out. The figure shows the result of sixteen results that were published between 1982 and 2018. The large scatter compared to the reported uncertainty of the measurements is readily visible in the therein. The relative difference of the largest to the smallest numerical value is 5.5×10^{-4}. In contrast, the smallest self-reported 1-σ error is 11.7×10^{-6} and the largest 148×10^{-6}. Hence, the span of the data is between 3.7 and 47.2 times the relative uncertainty of the individual experiments. Clearly, the data-set lacks internal consistency.

Having all these groups working on the measurement of a single value infused a lot of energy into the field. Many articles were published, several conferences were held, and fun ideas were developed. As is shown in the figure many results were published. However, the data is still not sufficiently consistent. So, why is that?

The reason the results are not consistent is, because these measurements are hard. As of 2025, the current accepted value of the gravitational constant is

$$G = (6.674\,30 \pm 0.000\,15) \times 10^{-11}\ \mathrm{m^3 kg^{-1} s^{-2}}. \tag{1}$$

In this talk, a narrative arc from the historical beginnings of the different methods to their modern implementation is given. Finally, a brief overview of the current state-of-the-art and an outlook will be given.

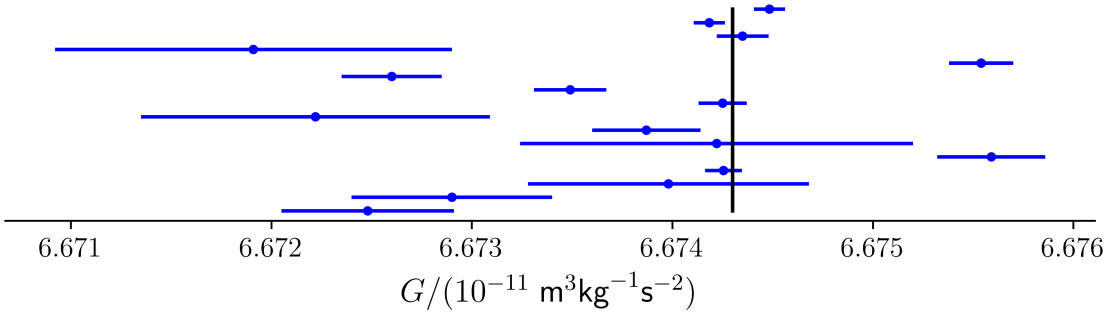

Figure 1: Measurements of the gravitational constant from 1982 (bottom) to 2018 (top). The numerical value recommended by the Committee on Data for Science and Technology (CODATA) is given by the black vertical line. The horizontal lines denote $1-\sigma$ uncertainties that were self reported by the researchers. Clearly the scatter between the data is larger than one would expect based on the reported uncertainties.

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Muon $g-2$: Theory Review

Andrzej Czarnecki [1, †]

[1]Department of Physics, University of Alberta, Edmonton, Alberta, Canada T6G 2E1
†corresponding author's email: andrzejc@ualberta.ca

The anomalous magnetic moment of the muon, $a_\mu = (g-2)/2$, has been used to test the Standard Model (SM) and to search for New Physics for more than six decades. I will begin by recalling why the gyromagnetic factor g is close to 2 and how quantum corrections lead to an anomalous contribution. I will discuss possible interpretations of deviations from $g = 2$ and compare the g-factors of the electron and muon. The main part of the talk will be devoted to the SM contributions to a_μ, with particular focus on hadronic effects and the methods used to determine them. I will compare the resulting SM prediction with the latest measurement from the Fermilab experiment and briefly discuss the implications for new physics searches.

Acknowledgments

This research is supported by the Natural Sciences and Engineering Research Council of Canada (NSERC).

On the tenth-order QED contribution to the electron anomalous magnetic moment

Tatsumi Aoyama [1,], **Masashi Hayakawa** [2,4], **Akira Hirayama** [3], **Makiko Nio** [3,4 †]

[1]Institute for Solid State Physics, University of Tokyo, Kashiwa, 277-8581 Japan
[2]Department of Physics, Nagoya University, Nagoya, 464-8602 Japan
[3]Department of Physics, Saitama University, Saitama, 338-8570 Japan
[4]Nishina Center, RIKEN, Wako, 351-0198 Japan
†corresponding author's email: nio@riken.jp

The discrepancy of approximately 5σ between the two results for the tenth-order QED contribution to the electron $g-2$ has been recently resolved[1]. We report the details of this resolution.

The contribution from the tenth-order QED Feynman vertex diagrams without fermion loops was first reported in 2012 and later updated by the group led by T. Kinoshita, referred to as AHKN. No alternative calculation existed until S. Volkov independently evaluated the contribution from the same set of Feynman diagrams in 2019 and again in 2024[2]. Both AHKN and Volkov used Feynman parametric representations to express the integrands derived from Feynman diagrams and then numerically evaluated the integrals using the Monte-Carlo integration method. The discrepancy of the results of the coefficient of $(\alpha/\pi)^5$ between AHKN and Volkov was found to be 0.78 ± 0.15, corresponding to a significance of 5.2σ.

In AHKN's calculation, the Feynman vertex diagrams sharing the same photon corrections were summed using the Ward-Takahashi identity. As a result, 389 independent integrals collectively represent the contribution of 6,354 Feynman vertex diagrams. Ultraviolet (UV) divergences were handled by counterterms generated through the $\mathbb{K}$ operation, a power-counting rule in Feynman parametric space.

In contrast, Volkov directly calculated 3,213 vertex diagrams, which are independent under the time-reversal symmetry of QED. The UV counterterms were carefully chosen to ensure that the wave-function and vertex renormalization constants satisfy the Ward-Takahashi identity.

Because of differences in calculation methods, a direct diagram-by-diagram comparison between AHKN and Volkov is not straightforward. To bridge this gap, we expressed the difference in the Ward-Takahashi summed contributions in terms of the symbolic forms involving the lower-order quantities. Once the numerical values of these lower-order quantities were obtained, we performed a numerical comparison of the 389 results between the two approaches.

No significant discrepancies were found for individual results. However, the numerical differences in the 98 Ward-Takahashi summed contributions, originating from diagrams sharing a common structure, were not randomly distributed. The accumulation of these differences led to the observed 5σ discrepancy.

To address this, a recalculation with increased statistics in the Monte Carlo integration was performed for AHKN's 98 integrals. By replacing the previous values with the updated ones, we obtained a revised result, which is consistent with Volkov's result, thereby resolving the discrepancy.

Acknowledgments

We deeply acknowledge the late Professor Toichiro Kinoshita, whose research on the QED lepton $g-2$ laid the foundation for this work.

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Coulomb corrections to the two-loop vacuum polarization potential and their contribution to the Lamb shift of hydrogenlike ions

Sergey Volkov [1, †], **Vladimir A. Yerokhin** [1], **Zoltán Harman** [1], **Christoph H. Keitel** [1]

[1] Max Planck Institute for Nuclear Physics, Saupfercheckweg 1, D 69117 Heidelberg, Germany
†corresponding author's email: sergey.volkov.1811@gmail.com

The QED vacuum polarization potential corrections of orders $\alpha^2(Z\alpha)^3$ and $\alpha^2(Z\alpha)^5$ around a point charge were calculated. The values for arbitrary transferred momentum were obtained in tabular form. The results of order $\alpha^2(Z\alpha)^3$ agree with the previously calculated value [1] at zero momentum; the ones of order $\alpha^2(Z\alpha)^5$ were computed for the first time.

The obtained results improve the accuracy of the 2-loop vacuum polarization Lamb shift corrections significantly, especially in heavy ions and exotic atoms.

The potential calculation is based on the free QED Feynman diagrams, where the Coulomb potential lines are treated as propagator lines. These diagrams may have up to 6 loops in terms of free QED, and the development of special methods is required to make the computation feasible. A method similar to the one used for calculating the 5-loop free electron g-2 [2] was employed. The following topics are the subject of consideration: the principle of the reduction to finite integrals, renormalization and elimination of intermediate infrared and ultraviolet divergences, Monte Carlo integration, realization on GPUs.

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Recent results from the Karlsruhe Tritium Neutrino Experiment (KATRIN) and the future atomic tritium source for KATRIN++

Magnus Schlösser [1, †] **for the KATRIN collaboration**

[1]Tritium Laboratory Karlsruhe, Institute of Astroparticle Physics, Karlsruhe Institute of Technology, Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany
†corresponding author's email: magnus.schloesser@kit.edu

The absolute value of the neutrino mass plays an important role in cosmology and is a critical missing parameter of the Standard Model. Studying the kinematics of beta decays offers a uniquely model-independent access to the neutrino mass, which is complementary to stringent constraints from neutrinoless double-beta decay and cosmological observations.

Using this method, the Karlsruhe Tritium Neutrino (KATRIN) experiment has improved the upper bound on the incoherent sum of neutrino masses down to $m_\beta < 0.45$ eV (90% C.L.), with its full data set, acquired by then end of 2025, targeting a final sensitivity of < 0.3 eV. To further improve this sensitivity down to the 0.05 eV level, which allows cross-validation of the other mass measurement approaches, and answer the question of normal or inverted neutrino mass ordering, fundamentally new technological developments are necessary.

The state-of-the-art KATRIN experiment employs a molecular tritium source, operating at approximately 10^{11} beta decays per second, alongside an integration filter possessing a filter width of $\Delta E = 2.7$ eV, and a background rate of 0.1 counts per second, attributed to the ionization of neutral Rydberg atoms within the spectrometer volume. Reaching down to inverted ordering with such a "KATRIN-like" configuration would necessitate either a significantly stronger source or a decades-long measurement program, both of which are impractical from a technical standpoint. In principle, any integral spectroscopy method, such as the MAC-E filter technique, is burdened by a measurement-time expansion-factor of $O(30)$, due to its point-by-point nature, in contrast to a truly differential measurement that captures the entire spectrum simultaneously. Substantial improvement in neutrino-mass sensitivity could be realized by transitioning to a detection method employing high-resolution differential measurement techniques. However, such a differential method needs to achieve an energy resolution of well below 1 eV (FWHM). This approach would outperform the current integrating MAC-E filter by using statistics more efficiently, as the energy of individual electrons is measured. In particular, it allows for the distinction between signal electrons and those originating from known backgrounds. Both are boosting the prospect of improved sensitivity.

Current research and development efforts in the KATRIN context focus on (i) time-of-flight measurements and (ii) large arrays of quantum sensors.

To further enhance neutrino-mass sensitivity in future experiments, atomic tritium must replace the current molecular tritium-based β-electron source. The β-decay of molecular tritium, $T_2 \rightarrow {}^3HeT^+ + e^- + \overline{\nu}_e$, differs from that of atomic tritium, $T \rightarrow {}^3He^+ + e^- + \overline{\nu}_e$, primarily in the final state spectrum of the daughter molecular ion, ${}^3HeT^+$. Moreover, molecular tritium decay leaves only 57% of daughter molecules in the electronic ground state, while atomic tritium decay increases this fraction to 70% for daughter atoms, boosting the number of relevant decay electrons near the spectral endpoint.

Additionally, ${}^3HeT^+$ remains in an excited ro-vibrational state, broadening the β-spectrum to approximately 1 eV (FWHM) and inherently limiting neutrino mass sensitivity, even with advanced detector resolutions. Moreover, electron scattering is less probable in atomic tritium than in T_2, reducing energy losses. Unlike T_2, the fermionic ($s = 1/2$) tritium atom can be manipulated using inhomogeneous magnetic fields, enabling trapping and cooling below the freeze-out temperature of T_2 to minimize Doppler broadening of β-decay electrons.

For implementation in KATRIN++, atomic tritium will be needed in copious amounts – comparable to the current molecular source of KATRIN – to achieve the required statistics. For this purpose, a large-scale demonstration experiment needs to be set up with the following goals: (a) Generation of large quantities of atomic tritium. (b) Development and implementation of effective atom cooling mechanisms. (c) Study of trapping times and maximum densities in a magnetic trap. (d) Investigation of the interplay of beta-driven plasma (meV-eV) and ultra-cold trapped atoms (neV).

We expect that the generation, cooling, and trapping of tritium atoms will suffer from low efficiencies in each step. Therefore, even for the demonstration experiment, macroscopic amounts of tritium must be used, which are estimated to be at the level of 10 g (T_2). This can only be done in a large-scale laboratory able to host and operate such a loop. The mission is to realize a global Atomic Tritium Pathfinder (ATP) at the Tritium Laboratory Karlsruhe (TLK). To achieve this, a joint working group is in the process of being formed. The partners for the ATP consortium will include those from various specialized areas: Neutrino mass partners such as KATRIN++, Project 8, and QTNM. In addition, partners from atomic and molecular physics, quantum gases, and precision spectroscopy are welcome to join this consortium.

A review of the Kibble balance technique for relating mass, force and torque to the Planck constant.

Ian A. Robinson

National Physical Laboratory, Hampton Road, Teddington, Middlesex, TW11 OLW, U.K.
email: ian.robinson@npl.co.uk

The 2019 revision of the SI fixed the numerical value of the Planck constant to define mass within the SI. Thus any technique, at any scale, which, previously, was able to measure the Planck constant in terms of mass, can now be used to measure mass in the SI without reference to a macroscopic artefact standard.

The Kibble balance technique, which relates virtual electrical and mechanical power, was first conceived at NPL in 1975 by Bryan Kibble. The world's first Kibble balance (originally called the moving-coil watt balance) : the NPL Mk I, was used to help unify the world's voltage measurement systems. By combining the Josephson and Quantum Hall effects it is possible to relate virtual electrical power to the Planck constant and time. This allowed the Kibble technique to measure the Planck constant and now, after the revision of the SI, allows the technique to measure SI mass, force and torque.

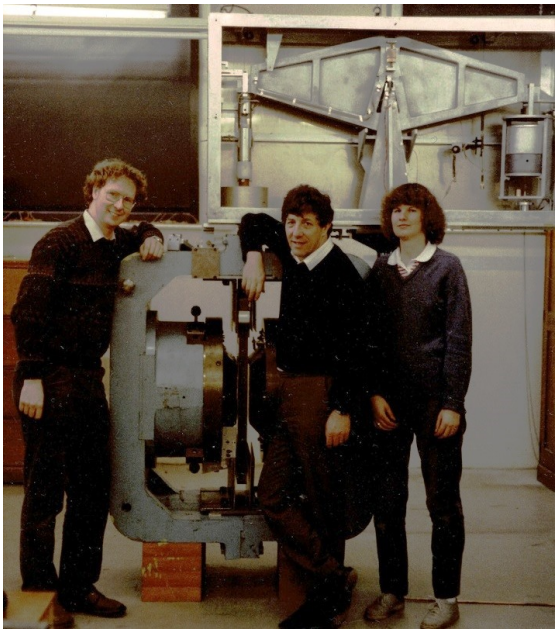

Figure 1: Ian Robinson, Bryan Kibble and Janet Belliss with the NPL Mk I Kibble balance.

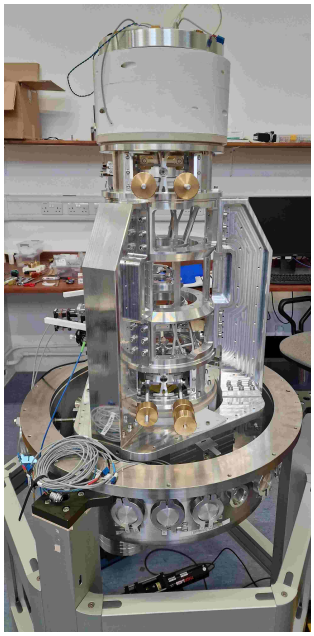

Figure 2: A "proof of concept" prototype of the NPL Next Generation Kibble balance.

Before the redefinition many National Measurement Institutes built Kibble balances for measuring the Planck constant and, after redefinition, these balances have been repurposed for realising the mass unit in the revised SI. Kibble balances with this aim are very expensive (costing many millions of Euros) but, for masses in the mg to μg range, large conventional measurement uncertainties arise from successive subdivision of the kg reference. In this case carefully designed Kibble balances, using conventional electrical standards can be used to make these measurements with improved accuracy and convenience. The technique can also measure force and torque, both statically and dynamically, and some laboratories have been developing instruments to work in these areas.

The technique has not stood still since it was conceived. BIPM proposed a new operating method and NPL has produced an extended theory which simplifies the operation of the balance under specific circumstances. Many laboratories have worked on novel forms of balance ensuring that the technique does not stagnate.

Future aims include making it easier for laboratories to make independent measurements at the highest level and also to make full use of the technique for smaller masses, forces and torques to support novel industrial applications.

Measurement of geometric distance between silicon spheres with laser interferometry in determination of G

Yanjie Zhang [1], **Tong Huang** [1], **Ruiqi Liu** [1], **Qing Li** [1, †]

[1]National Gravitation Laboratory, MOE Key Laboratory of Fundamental Physical Quantities Measurement, and School of Physics, Huazhong University of Science and Technology, Wuhan 430074, People's Republic of China
†corresponding author's email: qingli@hust.edu.cn

The time-of-swing method and the angular acceleration feedback method were used in our last measurement of G in 2018, both of which gave the values of G with an uncertainty of 12 ppm. In the two methods, the distances between the geometric centers of the source masses are the main error sources. For example, in the time-of-swing method, a 0.36 μm uncertainty of geometric distance introduces 9.3 ppm to the G value. If the measurement precision of the geometric distance can be reduced to 0.1 μm, its contribution to the G value is less than 1 ppm, so that it is no longer the main error source in the experiment.

In the on-going G measurement, the silicon spheres with more uniform density will be used. The roundness of the silicon spheres is expected to be 0.1 μm. The laser interferometry is used to measure the geometric distances between the spheres, which is a non-contact measurement method, has a very high precision, and can be carried out on the site to improve the reliability of measurement result. So far, the apparatus of measuring the geometric distances has been built. The measurement principle is analyzed, and the error sources, such as the laser, the sphere, the alignment of optical path, and the environment are evaluated. The measurement uncertainties of the horizontal and vertical geometric distances reach 11 nm and 9 nm, respectively. In the next step, the silicon spheres will be processed with great care, and the on-going G measurement is expected to give a new result in a few years.

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FRIDAY

May 30th, 2025

Towards a ^{229}Th nuclear optical clock

Maksim Okhapkin [1, †], Johannes Tiedau [1], Ke Zhang [1], Gregor-Alexander Zitzer [1], Vishal Lal [1], Shiv Sagar Maurya [1], Niels Irvin [1], Ekkehard Peik [1], Fabian Schaden [2], Thomas Riebner [2], Ira Morawetz [2], Luca Toscani De Col [2], Georgy Kazakov [2], Kjeld Beeks [2], Tomas Sikorsky [2], Thorsten Schumm [2].

[1] Physikalisch-Technische Bundesanstalt, Braunschweig, Germany
[2] Vienna Center for QuantumScience and Technology, Atominstitut, TU Wien, Vienna, Austria
† corresponding author's email: maksim.okhapkin@ptb.de

The first laser excitation of the ^{229}Th isomer state at 8.4 eV [1] and its quick confirmation in various solid-state environments [2, 3, 4] has inspired numerous proposals for applications, focusing on a nuclear optical clock that could potentially outperform atomic clocks based on electronic transitions [5, 6] and new physics because the transition frequency is strongly influenced by both the nuclear and electromagnetic forces [7].

We provide several experiments for the development of optical nuclear clocks based on thorium ions in an ion trap and in Th-doped crystals.

Enabling the realization of a solid-state nuclear clock we demonstrate laser-induced quenching as a method of depopulating the ^{229}Th isomeric state in CaF_2. This shortens a solid-state clock interrogation cycle and improves its performance [8].

We also will report ongoing experiments for the laser excitation of the isomeric state in $229Th^{2+}$ ions and the investigation of the hyperfine structure of sympathetically cooled Th^{3+} ions confined in linear Paul traps.

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New physics searches with highly charged ions: Nonlinear calcium King plot constrains new bosons and nuclear properties

Alexander Wilzewski [1,†], Luca I. Huber [2], Menno Door [3], Jan Richter [4], Agnese Mariotti [4], Lukas J. Spieß [1], Malte Wehrheim [1], Shuying Chen [1], Steven A. King [1], Peter Micke [1], Melina Filzinger [1], Martin R. Steinel [1], Nils Huntemann [1], Erik Benkler [1], Piet O. Schmidt [1], Jeremy Flannery [2], Roland Matt [2], Martin Stadler [2], Robin Oswald [2], Fabian Schmid [2], Daniel Kienzler [2], Jonathan Home [2], Diana P. L. Aude Craik [2], Sergey Eliseev [3], Pavel Filianin [3], Jost Herkenhoff [3], Kathrin Kromer [3], Klaus Blaum [3], Vladimir A. Yerokhin [3], Igor A. Valuev [3], Natalia S. Oreshkina [3], Chunhai Lyu [3], Sreya Banerjee [3], Christoph H. Keitel [3], Zoltán Harman [3], Julian C. Berengut [5], Anna Viatkina [1,6], Jan Gilles [1,6], Andrey Surzhykov [1,6], Michael K. Rosner [3], José R. Crespo López-Urrutia [3], Elina Fuchs[1,4]

[1]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany
[2]Institute for Quantum Electronics, Department of Physics, Eidgenössische Technische Hochschule Zürich, Otto-Stern-Weg 1, 8093 Zürich, Switzerland
[3] Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany
[4] Institut für Theoretische Physik, Leibniz Universität Hannover, Appelstraße 2, 30167 Hannover, Germany
[5] School of Physics, University of New South Wales, Sydney, NSW 2052, Australia
[6] Institut für Mathematische Physik, Technische Universität Braunschweig, D-38116 Braunschweig, Germany
[†] corresponding author's email: alexander.wilzewski@quantummetrology.de

Highly charged ions (HCI) are promising candidates for novel optical clocks and tests of fundamental physics [1]. Typically, the megakelvin-temperature environment in which HCI are produced hinders high-precision spectroscopy. To overcome this, we extract HCI from an electron beam ion trap and transfer them to a cryogenic linear Paul trap. There, single HCI are sympathetically cooled by Be^+ ions down to millikelvin temperatures, thus enabling quantum logic state readout [2]. In this way, we developed an optical clock based on Ar^{13+} and determined its absolute frequency with sub-Hz uncertainty by comparison with the Yb^+ octupole ion clock at PTB [3]. We recently applied these techniques to determine the isotope shift of a narrow magnetic-dipole transition in Ca^{14+} with 150 mHz accuracy for all five even and stable isotopes ^{40,42,44,46,48}Ca. We combine these results with recently improved measurements of isotope shifts in Ca^+ conducted at ETH Zürich and more precise measurements of nuclear mass ratios performed at MPIK Heidelberg in a so-called King plot. To first order, the standard model predicts a linear King plot. However, nonlinearities can arise from higher-order effects or a new force that would couple electrons and neutrons. For the first time, we observe a $\sim 900\sigma$ nonlinearity in the King plot of Ca and identify two standard model effects as its potential sources: the second-order recoil shift and the nuclear polarization effect. Despite the observed nonlinearity, we derive improved constraints on a new force using the King plot method and argue that more precise calculations and additional isotope shift measurements could further tighten these constraints in the future [4].

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Fundamental physics with antihydrogen in the ALPHA experiment

Stefan Eriksson[1]

[1] Department of Physics, Faculty of Science and Engineering, Swansea University, Singleton Park, Swansea SA2 8PP
corresponding author's email: s.j.eriksson@swansea.ac.uk

Precision measurements of trapped antihydrogen offer stringent tests of fundamental principles underlying particle physics and general relativity, such as Lorentz and CPT invariance, and the Einstein Equivalence Principle. In this presentation I will give an introduction to how precise measurements of the anti-atom are interpreted as tests of fundamental physics. I will present an overview of the ALPHA antihydrogen experiment at CERN including the most recent advances in antihydrogen synthesis, trapping and results from recent antiproton runs. I will conclude with a brief outline of the prospects for future high-precision experiments with antihydrogen.

Spin-dependent exotic interactions

Lei Cong [1,2,3,4, †,*], **Wei Ji** [1,2,3,5, †,*], **Pavel Fadeev** [3], **Filip Ficek** [6,7], **Min Jiang** [8,9], **Victor V. Flambaum** [10], **Haosen Guan** [11], **Derek F. Jackson Kimball** [12], **Mikhail G. Kozlov**, **Yevgeny V. Stadnik** [13], **Dmitry Budker** [1,2,3,14]

[1]Helmholtz Institute Mainz, 55099 Mainz, Germany
[2]GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany
[3]Johannes Gutenberg University, Mainz 55128, Germany
[4]International Center of Quantum Artificial Intelligence for Science and Technology (QuArtist) and Department of Physics, Shanghai University, 200444 Shanghai, China
[5]School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China.
[6]Faculty of Mathematics, University of Vienna, Oskar-Morgenstern-Platz 1, 1090 Vienna, Austria
[7]Gravitational Physics Group, University of Vienna, Währinger Straße 17, 1090 Vienna, Austria
[8]CAS Key Laboratory of Microscale Magnetic Resonance and School of Physical Sciences, University of Science and Technology of China, Hefei, Anhui 230026, China
[9]CAS Center for Excellence in Quantum Information and Quantum Physics, University of Science and Technology of China, Hefei, Anhui 230026, China
[10]School of Physics, University of New South Wales, Sydney, New South Wales 2052, Australia
[11]University of Science and Technology of China, Hefei, Anhui 230026, China
[12]Department of Physics, California State University – East Bay, Hayward, California 94542-3084, USA
[13]School of Physics, The University of Sydney, Sydney, New South Wales 2006, Australia
[14]Department of Physics, University of California at Berkeley, Berkeley, California 94720-7300, USA
†corresponding author's email: congllzu@gmail.com; wei.ji.physics@gmail.com;
* Equal contribution.

Novel interactions beyond the four known fundamental forces in nature (electromagnetic, gravitational, strong and weak interactions), may arise due to "new physics" beyond the standard model, manifesting as a "fifth force". This review is focused on spin-dependent fifth forces [1] mediated by exotic bosons such as spin-0 axions and axionlike particles and spin-1 Z' bosons, dark photons, or paraphotons. Many of these exotic bosons are candidates to explain the nature of dark matter and dark energy, and their interactions may violate fundamental symmetries. Spin-dependent interactions between fermions mediated by the exchange of exotic bosons have been investigated in a variety of experiments, particularly at the low-energy frontier. Experimental methods and tools used to search for exotic spin-dependent interactions, such as atomic comagnetometers, torsion balances, nitrogen-vacancy spin sensors, and precision atomic and molecular spectroscopy, are described. A complete set of interaction potentials, derived based on quantum field theory with minimal assumptions and characterized in terms of reduced coupling constants, are presented. A comprehensive summary of existing experimental and observational constraints on exotic spin-dependent interactions is given, illustrating the current research landscape and promising directions of further research.

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Measuring the ground state hyperfine splitting of antihydrogen in the ALPHA experiment

Timothy Friesen [1, †]

[1]Department of Physics and Astronomy, University of Calgary, Calgary, Canada
†corresponding author's email: timothy.friesen@ucalgary.ca

The matter-antimatter asymmetry problem remains one of the biggest unresolved questions in physics. Antihydrogen, as the simplest purely antimatter atomic system, provides a natural platform for testing CPT symmetry and potentially shedding light on this mystery. Precise measurements of antihydrogen's transition frequencies, compared to their well-established counterparts in hydrogen, offer a stringent test of CPT symmetry in the atomic sector. In particular, microwave spectroscopy of the ground-state hyperfine splitting presents a promising avenue. In hydrogen, this transition has been measured to a precision of 1×10^{-12} [1] and an absolute precision of 2 mHz (compared to 10 Hz for the 1S – 2S transition).

The ALPHA collaboration at CERN has been leading the way in testing fundamental symmetries using magnetically trapped antihydrogen. Recent breakthroughs include precision spectroscopy of the 1S–2S transition [2], fine structure measurements [3], laser cooling of antihydrogen [4], and the first-ever gravitational free-fall study of antihydrogen [5]. Advances in magnetic field control and enhanced antihydrogen trapping rates, enabled by Be+ ion assisted antihydrogen production, have also opened new possibilities for microwave spectroscopy. In this talk, I will present ALPHA's latest hyperfine spectroscopy experiments and discuss prospects for even higher precision measurements in the near future.

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High-precision ground-state fine and hyperfine spectroscopy at µTEx

Andreas Mooser [1, †], **Stefan Dickopf** [1], **Anton Gramberg** [1], **Philipp Justus** [1], **Annabelle Kaiser** [1], **Ankush Kauschik** [1], **Marius Müller** [1] **Stefan Ulmer**[2,3], **Klaus Blaum** [1]

[1]Max-Planck-Institute for Nuclear Physics, Heidelberg, Germany
[2]Heinrich-Heine University Düsseldorf, Germany
[2]RIKEN, Wako, Japan
†corresponding author's email: Andreas.Mooser@mpi-hd.mpg.de

At our Penning-trap experiment µTEx in Heidelberg, Germany, we measure the ground-state fine- and hyperfine-structure splitting of light, hydrogenlike ions and nucleons in a magnetic field [1]. From the measured transitions, the bound electron and shielded nuclear g-factors as well as the hyperfine-structure constant are extracted. In comparison with theory calculations, this allows to test QED, to infer charge radii of nuclei and to precisely determine fundamental constants such as the electron mass and nuclear magnetic moments. Comparisons to additional lithiumlike measurements allow testing of nuclear magnetic shielding theory. The results of the latest ^{9}Be campaign [2] as well as ongoing measurements and future plans will be presented.

This work is part of and funded by the Max Planck Society and RIKEN. Furthermore, this project has received funding from the European Research Council, the International Max Planck Research School for Precision Tests of Fundamental Symmetries and the Max Planck-RIKEN-PTB Center for Time, Constants and Fundamental Symmetries.

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BASE – testing fundamental symmetries by high precision comparisons of the fundamental properties of protons and antiprotons

B. M. Latacz [1, †], **F. Abbass** [2], **B. P. Arndt** [3,4], **S. Endoh** [5,6], **S. Erlewein** [2], **P. Geissler** [5], **J. I. Jäger** [3], **T. Imamura** [7], **M. Leonhardt** [2], **P. Micke** [1,3], **A. Mooser** [3], **D. Schweitzer** [2], **S. Stahl** [7], **A. M. Thomas** [2], **T. E. Tiemens** [8], **F. Voelksen** [2], **H. Yildiz** [3], **K. Blaum** [3], **J. A. Devlin** [9], **Y. Matsuda** [6], **C. Ospelkaus** [7,10], **W. Quint** [4], **A. Soter** [8], **J. Walz** [11,12], **Y. Yamazaki** [5], **C. Smorra** [2], **S. Ulmer** [2,5]

[1]CERN, Department of Experimental Physics, Geneva, Switzerland
[2]Institut für Experimentalphysik, Heinrich Heine Universität Duesseldorf, Germany
[3]Max-Planck-Institut für Kernphysik, Heidelberg, Germany
[4]GSI-Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany
[5]RIKEN, Ulmer Fundamental Symmetries Laboratory, Wako, Saitama, Japan
[6]Graduate School of Arts and Sciences, University of Tokyo, Tokyo, Japan
[7]Institut für Quantenoptik, Leibniz Universität, Hannover, Germany
[8]ETH-Zürich, Zürich, Switzerland
[9]Center for Cold Dark Matter, Blackett Laboratory, Imperial College London, United Kingdom
[10]Physikalisch-Technische Bundesanstalt, Braunschweig, Germany
[11]Institut für Physik, Johannes Gutenberg-Universität, Mainz, Germany
[12]Helmholtz-Institut Mainz, Johannes Gutenberg-Universität, Mainz, Germany
†corresponding author's email: barbara.latacz@cern.ch

BASE is an international collaboration focused on testing CPT invariance by performing ultra-precise measurements of the fundamental properties of antibaryons and baryons.

In this talk, we will focus on our flagship experiment at CERN which is dedicated to measure the antiproton and proton magnetic moments. To date, determined these quantities with a fractional resolution of 1.5 p.p.b. [1] and 300 p.p.t. [2], respectively. We will report on the status of the current measurement campaign with the goal to improve the fractional accuracy of the antiproton magnetic moment by at least a factor of 10. An important ingredient is the development of a new cooling trap, which provides orders of magnitude improved cyclotron-mode cooling which resulted in error-free, non-destructive antiproton spin quantum transition spectroscopy [3]. Additionally, we will present the first implementation of coherent spin-state spectroscopy of a single antiproton spin, enabling measurements at 16-fold narrower line-width than in previous experiments. Finally, we will summarize the status of improved measurements.

Currently, the precision of our experiments is limited by magnetic noise in the accelerator hall. To overcome this limitation, we have developed an open Penning trap system, BASE-STEP [4], which will enable the transport of antiprotons to fully equipped offline laboratories at Heinrich Heine University Düsseldorf and CERN. In the stable environment of these new laboratories, we aim to achieve measurements at 100-fold improved precision.

Additionally, we are currently developing new measurement techniques that will allow us to continue operating the experiment in the accelerator hall. To that end, we will implement synchronized cyclotron frequency measurements on two-particles, simultaneously trapped on magnetron-locked orbits.

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g-factor of H^-

Tymon Kilich [1, †], **Krzysztof Pachucki** [1]

[1]Faculty of Physics, University of Warsaw, ul. Pasteura 5, 02-093 Warszawa, Poland
†corresponding author's email: Tymon.Kilich@fuw.edu.pl

Nuclear magnetic shielding of a closed-shell atom can be expressed as the coupling of nuclear magnetic moment $\vec{\mu}$ with a homogeneous magnetic field $\vec{B}$ modified by the presence of atomic electrons, which is expressed in terms of the nuclear magnetic shielding constant σ

$$\delta H = -\vec{\mu} \cdot \vec{B}(1-\sigma). \tag{1}$$

The most accurate theoretical predictions of nuclear magnetic shielding for light atomic and molecular systems can be obtained using NRQED theory [1, 2, 3]. In this theory, the nuclear magnetic shielding constant σ is expanded as a double series in the fine-structure constant α and the electron–nucleus mass ratio m/m_n

$$\sigma = \sigma^{(2,0)} + \sigma^{(2,1)} + \sigma^{(2,2)} + \sigma^{(4,0)} + \sigma^{(4,1)} + \sigma^{(5,0)} + \sigma^{(6,0)} + \dots \tag{2}$$

where $\sigma^{(n,k)} \propto \alpha^n (m/m_n)^k$ in $\hbar = c = \epsilon_0 = 1$ units.

In this work, we present highly accurate calculations of the nuclear magnetic shielding constant of the ground state of the hydride ion (H^-). We calculate the relativistic $\sigma^{(4,0)}$ and (very often neglected) nuclear recoil $\sigma^{(2,1)}, \sigma^{(2,2)}$ corrections to the shielding constant. The latter are of particular importance in the H^- system because they are more significant than the relativistic effects. Including all these effects allows us to achieve a relative accuracy exceeding 10^{-9} for the nuclear magnetic shielding of the H^- system.

Acknowledgments

The work was supported by the National Science Centre, Poland, under research project no. 2018/29/N/ST4/02034.

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A slow beam of antihydrogen atoms

D. J. Murtagh [1, †]
on behalf of the ASACUSA Cusp collaboration

[1]Stefan Meyer Institute for Subatomic Physics, Wiesingerstraße 4, 1010 Vienna, Austria
†corresponding author's email: daniel.murtagh@oeaw.ac.at

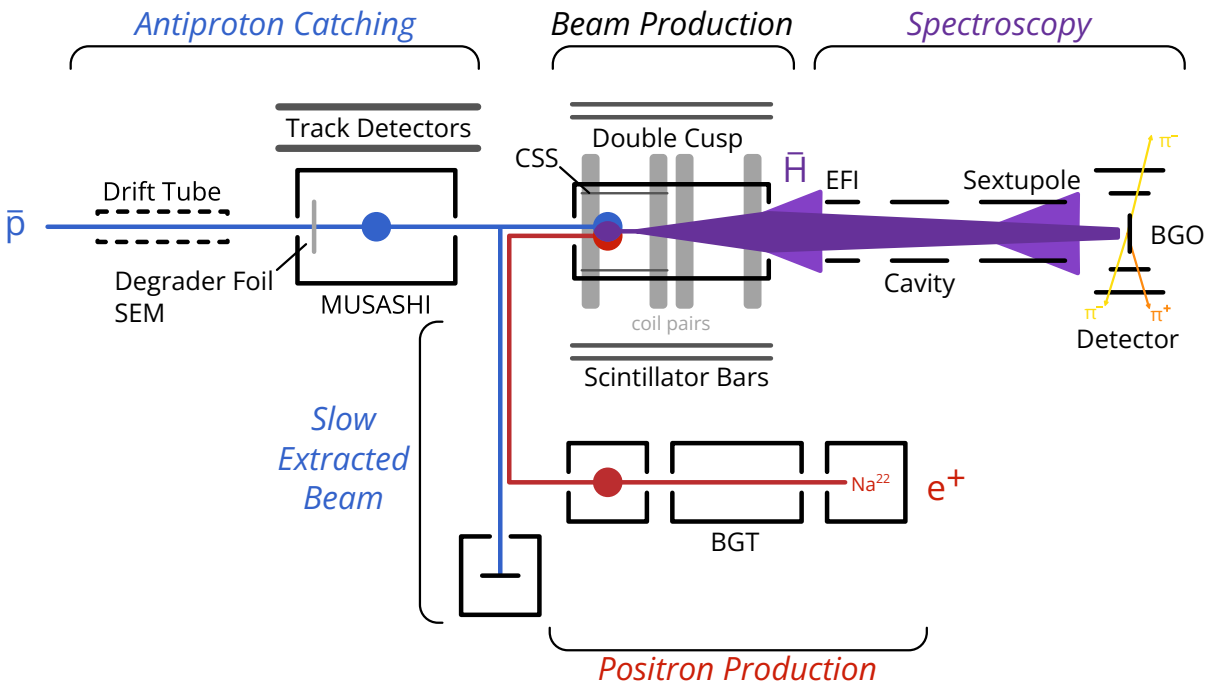

Figure 1: Schematic diagram of the ASACUSA-Cusp experiment. Positron and antiproton plasmas (red and blue circles) are combined in the Double Cusp to form an antihydrogen beam (purple).

The ASACUSA-Cusp experiment aims to measure the ground-state hyperfine structure of antihydrogen in a low magnetic field region using Rabi spectroscopy [1, 2]. A schematic diagram of the apparatus is shown in Figure 1. To perform this measurement, a spin-polarised beam of antihydrogen atoms is required. These atoms are produced in the Double Cusp trap [4, 3]. The beam passes through a microwave cavity, where the spectroscopy is performed, followed by a sextupole magnet for spin-selective focusing onto the antihydrogen detector.

ASACUSA produces antihydrogen by slowly combining large quantities of positron and antiproton plasma. The antiprotons are "mixed" with the positrons for 60 seconds, during which approximately 100 antihydrogen atoms leave the trap as a beam. These atoms are mostly in Rydberg states (principal quantum number $n > 20$) and can be ionised by a strong electric field. We study the binding energy of the atoms by varying the strength of this field, and we measure their time of flight by pulsing the field to chop the beam.

This presentation will cover our most recent measurements, as well as progress toward producing a slower beam with a higher fraction of ground-state atoms. Such a beam will enable us to achieve our aim of measuring the ground-state hyperfine splitting of antihydrogen in a low magnetic field with ppm precision.

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Muon Precision Measurement with the Penning Trap at J-PARC

Shoichiro Nishimura [1,2,†], Yukinori Nagatani [1,2], Takayuki Yamazaki [1,2], Patrick Strasser [1,2], Koichiro Shimomura [1,2], Ken-ichi Sasaki [1,2], Masatoshi Hiraishi [1,2], Amba Dat Pant [1,2], Hiroto Kokubo [3], Hiromi Iinuma [3], Taihei Adachi [4], Makiko Nio [4], Hirotaka Okabe [5], Takashi Higuchi [6]

[1]High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki, Japan
[2]J-PARC Center, Tokai, Ibaraki, Japan
[3]Graduate School of Science and Engineering, Ibaraki University, Mito, Ibaraki, Japan
[4]RIKEN Nishina Center for Accelerator-Based Science, Wako, Saitama, Japan
[5]Institute for Materials Research (IMR), Tohoku University, Sendai, Miyagi, Japan
[6]Institute for Integrated Radiation and Nuclear Science, Kyoto University, Kumatori, Osaka, Japan
†corresponding author's email: shoichiro.nishimura@kek.jp

Muon precision measurements constitute a powerful probe in the search for new physics beyond the Standard Model of particle physics. A prominent example is the measurement of the muon anomalous magnetic moment $(g-2)$, which exhibits a 4.2σ discrepancy between theoretical predictions and experimental results. This deviation is regarded as a potential indication of new physics [1]. In previous precision measurements, muons were either in an accelerated state or in a muonium state.

In this study, a novel method is proposed to precisely measure slow free muons by confining them in an electromagnetic field utilizing the Penning trap technique. This represents the first application of a Penning trap to particles with lifetimes as short as that of muons (2.2 μs). The experiment will be conducted using the high-intensity pulsed muon beam at J-PARC H-Line [2]. The ultimate goal is to measure the muon mass and magnetic moment with a precision of 1 ppb and the muon lifetime with a precision of 1 ppm.

A schematic representation of the experimental setup is provided in Fig. 1. Muons are initially injected into a degrader or an ultra-slow muon-producing target within a 3 T superconducting magnet to decelerate them. The resulting slow or ultra-slow muons are subsequently transported to the trap region via an electric field. During transport, an RF magnetic field is applied to rotate their spin direction by $\pi/2$, aligning it perpendicular to the magnetic field to facilitate the observation of Larmor precession. The muon spins and positions are precisely controlled by the electromagnetic field, and their oscillation frequencies are measured using upper and lower detectors via the detection of decay electrons or positrons.

At present, the development of electrodes, which are integral to the trap, as well as detectors for measuring rapid spin precession, is underway. The current status of these developments will be reported.

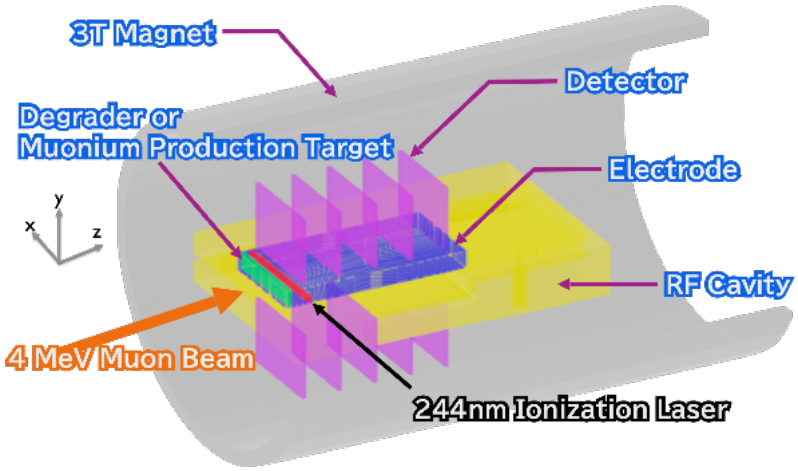

Figure 1: Schematic view of the muon trap experiment.

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The n2EDM experiment at the Paul Scherrer Institute

Wenting Chen [1,2] †**, on behalf of the nEDM collaboration**

[1]PSI Center for Neutron and Muon Sciences, Paul Scherrer Institute, CH-5232 Villigen PSI, Switzerland
[2]ETH Zürich, Institute for Particle Physics and Astrophysics, CH-8093 Zürich, Switzerland
†corresponding author's email: wenting.chen@psi.ch

High-precision measurements of the permanent electric dipole moment (EDM) could provide crucial information for probing charge-parity (CP) violation and exploring physics Beyond the Standard Model. The n2EDM experiment, carried out by the international nEDM collaboration at the ultracold neutron source of the Paul Scherrer Institute, searches for a neutron EDM with a sensitivity of $1 \times 10^{-27}\, e\,$cm in the baseline setup. This represents an order of magnitude improvement over the current experimental limit measured with our previous apparatus at PSI [1].

This talk will provide an overview of the experiment and measurement method, and present preliminary results from the ongoing commissioning. First physics data taking is planned to start in 2025.

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This work is supported by the Swiss National Science Foundation Project 204118.

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Variation of the Quadrupole Hyperfine Structure and Nuclear Radius due to an Interaction with Scalar and Axion Dark Matter

Victor Flambaum [1], **Andrew Mansour** [1, †]

[1]School of Physics, University of New South Wales, Sydney 2052, Australia
†corresponding author's email: andrew.mansour@student.unsw.edu.au

Atomic spectroscopy is used to search for the space-time variation of fundamental constants which may be due to an interaction with scalar and pseudoscalar (axion) dark matter. In this letter, we study the effects which are produced by the variation of the nuclear radius and electric quadrupole moment. The sensitivity of the electric quadrupole hyperfine structure to both the variation of the quark mass and the effects of dark matter exceeds that of the magnetic hyperfine structure by 1-2 orders of magnitude. Therefore, the measurement of the variation of the ratio of the electric quadrupole and magnetic dipole hyperfine constants is proposed. The sensitivity of the optical clock transitions in the Yb^+ ion to the variation of the nuclear radius allows us to extract, from experimental data, limits on the variation of the hadron and quark masses, the QCD parameter θ and the interaction with axion dark matter.

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Ultracold molecules - a testbed for physics beyond the Standard Model

Adam Koza [1], **Alessio Ciamei** [2,3], **Michał Tomza** [1 †]

[1]Faculty of Physics, University of Warsaw, Pasteura 5, 02-093 Warsaw, Poland
[2]Istituto Nazionale di Ottica del Consiglio Nazionale delle Ricerche (CNR-INO), 50019 Sesto Fiorentino, Italy
[3]European Laboratory for Non-Linear Spectroscopy (LENS), Universit'a di Firenze, 50019 Sesto Fiorentino, Italy
†corresponding author's email: michal.tomza@fuw.edu.pl

The Standard Model of Particle Physics (SM) provides a good description of matter, radiation, and their interactions. Unfortunately, there are still open questions in science where SM cannot accurately describe observed phenomena such as the matter-antimatter imbalance. A promising approach to uncovering physics beyond the SM is to identify novel sources of combined charge and parity ($\mathcal{CP}$) violation. The presence of $\mathcal{P},\mathcal{T}$-odd forces and permanent electric dipole moments of elementary particles may induce a non-zero molecular dipole moment of the entire system, leading to subtle shifts in the molecule's energy structure [1]. In this work, we propose a new class of molecular systems – ultracold high-spin Σ-state polar molecules, such as YbCr and RaCr – as sensitive platforms to study $\mathcal{CP}$ violation in the hadronic and leptonic sectors. We theoretically modeled the formation of these molecules from ultracold high-spin spherically symmetric atoms with closed-shell atoms. We found that these systems can be easily polarized due to the presence of Ω doubling and used for precision measurements. We analyzed their molecular properties using relativistic *ab initio* quantum chemical methods. We carefully investigated enhancement factors describing the sensitivity of molecules to the $\mathcal{CP}$-odd nuclear magnetic quadrupole moment, electron electric dipole moment and electron-nucleon scalar-pseudoscalar interactions [2]. Possibility of the formation of YbCr [3] or RaCr in ultracold temperatures makes them great for high-precision experiments due to enhanced sensitivity of an experiment. In this manner, we want to pave the way for a new class of very promising systems for the next generation of SM-physics searches at the low-energy frontier.

Acknowledgments

We gratefully acknowledge the European Union (ERC, 101042989 – QuantMol), the National Science Centre, Poland, within Preludium (Grant No. 2024/53/N/ST2/03814) and the PL-Grid Infrastructure (Grant No. PLG/2023/016115)

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POSTERS

Gaussian basis set approach to one-loop self-energy

Dávid Ferenc [1, †], **Trond Saue** [1],

[1]Laboratoire de Chimie et Physique Quantique UMR 5626 CNRS—Université Toulouse III-Paul Sabatier 118 Route de Narbonne, F-31062 Toulouse, France

†corresponding author's email: david.ferenc@irsamc.ups-tlse.fr

The accurate computation of QED corrections to the energy levels of molecules, to all-orders in the external Coulomb potential, presents a significant challenge. The use of Gaussian basis sets is an essential ingredient in extending such calculations to polyatomic molecular systems. At the one-loop level, the corrections to the electron-nucleus interaction are vacuum polarization and the electron self-energy. The leading-order (in $Z\alpha$) vacuum polarization correction can be included in molecular computations as an effective local potential (Uehling potential) [1]. The computation of the complete many-potential vacuum polarization density was carried out recently in a Gaussian basis set [2]. The evaluation of the self-energy correction on the other hand is more involved. In this contribution, I present a method that combines the rigorous bound-state QED approach, the many-potential expansion, with a Gaussian basis set expansion to obtain accurate values for the one-loop self-energy correction in a hydrogen-like atom [3].

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Polarisation effects in microwave spectroscopy of Positronium

Krzysztof P. Habdas[1, †], **Rebecca J. Daly**[1], **Ross E. Sheldon**[1, ⋆], **David B. Cassidy** [1, ‡]

[1]Department of Physics and Astronomy, University College London, Gower Place, WC1E 6BN, London, United Kingdom
⋆ present address: Stefan Meyer Institute for Subatomic Physics, Austrian Academy of Sciences (ÖAW), Boltzmanngasse 3, 1090 Wien, Austria
†presenting author's email: k.habdas@ucl.ac.uk,
‡corresponding author's email: d.cassidy@ucl.ac.uk

Being composed only of leptons, positronium (Ps), the bound state of an electron and positron, is described almost entirely by quantum electrodynamics (QED) theory. Measurements of Ps energy intervals, decay rates, or decay modes can be used to test QED calculations, but due to various experimental challenges the measurement precision is considerably lower than the corresponding theoretical values [1, 2].

In the the Ps $n = 2$ fine structure, the precision of the calculated energy intervals is known to be 80 kHz, whereas the errors of the measured values are approximately 1 MHz [3, 4]. Recent measurements attempting to reduce this disparity have been performed using waveguides aligned perpendicularly to the beam axis, which is necessary because of the transverse velocity spread of typical Ps sources [2]. In this configuration, the direction of the electric field is such that only transitions for which $\Delta M_J = 0$ can be driven [5].

It is possible, however, to drive transitions with different microwave polarisations in free space, using a horn antenna to generate microwave radiation [6]. This approach has some limitations, such as reduced intensity of radiation and more complicated fields than are obtained in a waveguide [5], but it allows for varying of polarisation.

Here we present measurements of the $2\,^3S_1 \rightarrow 2\,^3P_1$ transition in positronium using microwave radiation generated using a horn antenna. By rotating the axis of the antenna, and hence the polarisation of the radiation, transitions were driven for which either the selection rule $\Delta M_J = 0$ or $\Delta M_J = \pm 1$ dominated. In both cases, good agreement was found with theory for the resonance frequencies and relative transition rates. We also demonstrate that previously observed frequency shifts, arising from reflections of microwave radiation within the vacuum chamber in which the measurements were performed, can be largely mitigated using a modified apparatus.

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Ortho-Positronium lifetime measurements with a new PET-like detector

Carlos Vigo [1], Lars Gerchow [2], Paolo Crivelli [1], Valentin Schmidt[1]

[1]Institute for Particle- and Astro- Physics, ETH Zürich, Otto-Stern-Weg 5, 8093 Zürich, Switzerland
[2]Institute of Pharmaceutical Sciences, ETH Zürich, Vladimir-Prelog-Weg 1-5/10, 8093 Zürich, Switzerland

Positronium, as a simple leptonic system, allows us to make precise QED predictions on its properties, such as its lifetime. Second-order loop corrections to the ortho-Positronium decay rate have been calculated, predicting the lifetime up to the 1ppm level [1]. Compared to the state-of-the-art measurements [2] [3], the theory is two orders of magnitude ahead in precision. As the main limitations so far are of systematic as well as statistical nature, we propose a new experiment that partly combines previous methodologies to measure the ortho-positronium decay rate in vacuum. The main systematic improvements lay in the new method to account for the pick-off of an electron from the cavity walls, after which the ortho-Positronium decays into 2 photons prior to its vacuum decay. This method will be possible with the usage of a new PET-like detector with a fine spatial resolution, high time, and energy resolution. A new design of a spatial confinement cavity for the positronium will be used and has been tested [4]. This will allow to reduce the systematic error by at least an order of magnitude. The setup at the ETH pulsed high intensity positron beam, together with a dedicated tagging system, further allows to obtain the sought-after statistics, and with that to reduce the statistical uncertainty to the region of comparability to the state of art calculations.
The status of the detector, preliminary measurements with this detector, and the detailed plan will be presented.

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Searching for Exotic Interactions between Antimatter

Lei Cong [1,2,3], **Filip Ficek** [4,5,†], **Pavel Fadeev** [3], **Yevgeny V. Stadnik** [6], **Dmitry Budker** [1,2,3,7,*]

[1]Helmholtz Institute Mainz, 55099 Mainz, Germany
[2]GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany
[3]Johannes Gutenberg University, Mainz 55128, Germany
[4]Faculty of Mathematics, University of Vienna, Oskar-Morgenstern-Platz 1, 1090 Vienna, Austria
[5]Gravitational Physics Group, University of Vienna, Währinger Straße 17, 1090 Vienna, Austria
[6]School of Physics, University of New South Wales, Sydney, New South Wales 2052, Australia
[7]Department of Physics, University of California at Berkeley, Berkeley, California 94720-7300, USA
†corresponding author's email: ficekf@gmail.com;
* corresponding author's email: budker@uni-mainz.de

We show that atomic antimatter spectroscopy can be used to search for new bosons that carry spin-dependent exotic forces between antifermions [1]. A comparison of a recent precise measurement of the hyperfine splitting of the 1S and 2S electronic levels of antihydrogen and bound-state quantum electrodynamics theory yields the first tests of exotic positron-antiproton interactions, constraining the dimensionless coupling strengths $g_p g_p$, $g_V g_V$ and $g_A g_A$, corresponding to the exchange of a pseudoscalar (axion-like), vector, or axial-vector boson, respectively. We also discuss new tests of CPT invariance with exotic spin-dependent and spin-independent interactions involving antimatter.

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Constraints on exotic interactions from scalar spin-spin coupling in tritium deuteride (DT)

Lei Cong [1,2,3], **Derek F. Jackson Kimball** [4], **Mikhail G. Kozlov**, **Dmitry Budker** [1,2,3,5,+]

[1]Helmholtz Institute Mainz, 55099 Mainz, Germany
[2]GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany
[3]Johannes Gutenberg University, Mainz 55128, Germany
[4]Department of Physics, California State University – East Bay, Hayward, California 94542-3084, USA
[5]Department of Physics, University of California at Berkeley, Berkeley, California 94720-7300, USA
+ corresponding author's email: budker@uni-mainz.de;

A comparison of theoretical and experimental values of the scalar spin-spin interaction (J-coupling) in tritium deuteride molecules yield constraints for nucleon-nucleon exotic interactions of the dimensionless coupling strengths $g_V g_V$, $g_A g_A$ and $g_p g_p$, corresponding to the exchange of an vector, axial-vector, and pseudoscalar (axionlike) boson. The couplings between proton (p) and nucleon (N), denoted by $g_V^p g_V^N$, $g_p^p g_p^N$ are constrained to be less than 1.4×10^{-6} and 2.7×10^{-6}, respectively, for boson masses around 5 keV. The coupling constant $g_A^p g_A^N$ is constrained to be less than 1.0×10^{-18} for boson masses $\leq$ 100 eV. It is noteworthy that this study represents the first instance in which constraints on $g_V g_V$ have been established through the analysis of the potential term V_2+V_3 for both tritium deuteride and hydrogen deuteride molecules.

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Pair corrections to the no-pair Dirac–Coulomb(–Breit) energy of heliumlike systems

Ádám Nonn [1, †], **Edit Mátyus** [1]

[1]Institute of Chemistry, Eötvös Loránd University,
Pázmány Péter sétány 1/A, H-1117 Budapest, Hungary
[†]corresponding author's email: nonnadam@student.elte.hu

The equal-time Bethe–Salpeter (Salpeter–Sucher) equation is used as a starting point for describing two-spin-1/2-fermion bound states [1, 2, 3, 13, 14]. The equation containing only the instantaneous part of the interaction is the with-pair Dirac–Coulomb(–Breit) equation (wpDC(B)), which includes the double-pair correction to the no-pair DC(B) equation (npDC(B)). The numerical results for these equations can be converged within ppb to ppt relative precision using an explicitly correlated Gaussian (ECG) basis set approach [4]-[12].

While the double-pair correction is a non-hermitian, but 'algebraic' term, which leaves the DC(B) equation linear in energy, the single-pair correction, represented by the irreducible crossed-Coulomb(–Breit) interaction kernel, appears within a complicated, energy-dependent operator in the Salpeter–Sucher equation. The inclusion of the crossed-Coulomb(–Breit) and other higher-order or radiative irreducible interaction kernels through this term renders the wave equation non-linear in energy.

A novel perturbative approach is therefore being considered for the treatment of these contributions, using the npDC(B) and wpDC(B) results as high-precision relativistic reference energies and wave functions [13, 14]. The results of this new relativistic QED (rQED) approach, including the single-pair correction, are expected to serve as a useful comparison to the well-established non-relativistic QED (nrQED) methodologies and the highest precision experimental results.

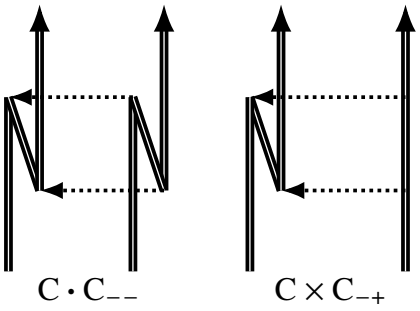

Figure 1: Time-ordered diagrams for the double-pair (left) and single-pair (right) corrections.

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Rovibronic computations of the b $^3\Pi_g$ and c $^3\Sigma_g^+$ electronic states of the helium dimer including the non-adiabatic, relativistic, and leading-order QED couplings and corrections

Balázs Rácsai [1] †, **Péter Hollósy** [1], **Péter Jeszenszki** [1], **Ádám Margócsy** [1], **Edit Mátyus** [1]

[1]ELTE, Eötvös Loránd University, Institute of Chemistry, Pázmány Péter sétány 1/A, Budapest, H-1117, Hungary
†rbrb@student.elte.hu

We report potential energy curves, diagonal Born–Oppenheimer, non-adiabatic mass, relativistic, and leading-order QED corrections for the b $^3\Pi_g$ and c $^3\Sigma_g^+$ electronic states of the helium dimer. Considering all non-adiabatic and relativistic couplings, we constructed the complete electronic-spin manifold of the b $^3\Pi_g$-c $^3\Sigma_g^+$-B $^1\Pi_g$-C $^1\Sigma_g^+$ states, enabling the computation of precise rovibrational energies for the b $^3\Pi_g$ and c $^3\Sigma_g^+$ states, including the fine structure and zero-field splittings.

Towards the self-energy correction of the no-pair Dirac–Coulomb energy for two-electron systems

Ádám Margócsy [1, †], **Edit Mátyus** [1]

[1]Faculty of Chemistry, Eötvös Loránd University, Pázmány Péter sétány 1/A, 1117 Budapest, Hungary
†corresponding author's email: adam.margocsy@ttk.elte.hu

Among the leading Quantum Electrodynamical (QED) corrections to atomic-molecular energy levels, the effect of one-loop electron self-energy has proven to be one of the most challenging to compute. There are well-established techniques to calculate it in two extreme cases (for predominantly non-relativistic [1, 2, 3, 4] and highly relativistic [5, 6, 7, 8, 9] systems, like low-charged and highly charged ions, respectively), but no general method to a correlated relativistic reference state is known.

Finding a self-energy calculating approach generally applicable regardless of the strength of relativistic effects is part of our ongoing research effort to build QED corrections on highly accurate relativistic two-particle wave functions [10, 11]. Our starting point is the equal-time formulation of the Bethe-Salpeter equation [12, 13], and its first approximation, the no-pair Dirac–Coulomb(–Breit) equation; radiative and non-radiative QED corrections are then included perturbatively.

In my poster, I present our current progress towards the calculation of self-energy with a relativistic two-electron wave function. The reference is a no-pair Dirac–Coulomb wave function obtained from an explicitly correlated variational procedure, providing an all-order description of (instantaneous, non-radiative) relativistic effects [14, 15]. An example calculation is given for the ground state of the helium atom.

Several questions are raised concerning the renormalization, the role of negative-energy states and permutational symmetry issues of inner states. A fully numerical renormalization scheme is proposed, reminiscent of partial wave renormalization [5, 6]. The new challenges and obstacles associated with the relativistic treatment of self-energy beyond the dipole approximation are discussed, with preliminary numerical results.

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QED effects in molecules : vacuum polarization in a Gaussian basis set

Ryan Benazzouk [1, †], **Maen Salman** [2], **Trond Saue** [1]

[1]Laboratoire de Chimie et Physique Quantique, CNRS, Université Toulouse III Paul Sabatier, Toulouse, F-31062 France
[2]Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS-Université PSL, Collège de France, Paris, F-75005, France

†corresponding author's email: ryan.benazzouk@irsamc.ups-tlse.fr

Recent developments have raised a new spark of interest for Quantum Electrodynamics (QED), from high-precision experiments to search for physics beyond the Standard Model. For instance, high-precision QED calculations for molecules could be of key importance in the search for new physics. As very intense electromagnetic fields are generated by heavy atoms inside molecules, the sensitivity of experiments probing for violations of the Standard Model predictions is greatly improved [1].

However, it is unclear to what extent QED can be relevant to describe molecular properties. It is now well known that relativistic effects play a prominent role in predicting properties of molecular systems containing heavy elements, and they can be computed to such high precision that correlation effects become the main source of error. But as correlation methods progress, the point approaches at which those effects compare with the magnitude of QED corrections [2]. One can then wonder if QED is needed for more precision in quantum chemistry, and to understand molecular structure or properties of the electronic density in the vicinity of heavy nuclei.

Before investigating this matter, some caveats need to be addressed. One has to do with the perturbative expansion of the S-matrix. This approach to QED has worked marvelously to clarify the reasons for divergences appearing in radiative loop-corrections, and their subsequent treatment. However, in the case of bound-state QED, the S-matrix should also be expanded in powers of the coupling constant to the nuclear potential $Z\alpha$, and this can become problematic when the coupling parameter approaches 1.

We should also mention that the S-matrix formalism deals rather poorly with electron correlation, as it requires very high orders of perturbation theory. Therefore, this approach may simply be too cumbersome for quantum chemistry, and one could aspire to a formulation of the theory that fits with the mathematical apparatus of molecular physics. Thankfully, such a program has already been proposed by Chaix & Iracane [3], and extensively studied by mathematicians [4, 5]: the Bogoliubov-Dirac-Fock model. The merit of this approach is that it yields a mean-field effective extension to the Dirac Hamiltonian that includes QED effects, reviving Dirac's interpretation of a negative energy sea, in a formalism akin to quantum chemistry. The QED effects, self-energy and vacuum polarization, arise respectively as an exchange and an electric potential generated by charge distribution in the polarized vacuum.

The goal of the HAMP-vQED project is therefore to provide a method for calculating QED effects on the electronic structure of molecules in the framework of quantum chemistry. Effective potentials already exist to target valence electrons, but we suspect that they might not be as reliable for core orbitals that undergo very intense electric fields. To do so, we then aim to compute vacuum polarization density and self-energy corrections using Gaussian-type basis sets [6, 7].

In this contribution, I will present my work on vacuum polarization in a finite basis, more specifically our results on energy shift calculations and our method for regularization. I will show how various aspects of vacuum polarization around a nucleus can be computed accurately in a finite Gaussian basis set.

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Prospects for a Precision Measurement of the Positronium $^1S_0 - ^3S_1$ Interval using Quantum Oscillations

Jia-Shian Wang †, **David Cassidy**

Department of Physics and Astronomy, University College London, Gower St, London WC1E 6BT, UK
†Presenter's email: josh.wang@ucl.ac.uk

Quantum oscillations, also known as quantum beating, are oscillatory behaviours in the physical observables of a quantum system, arising from the interference between non-degenerate energy eigenstates of the system. It was predicted that this effect should be observable in the three-photon annihilation decay of polarised positronium (Ps) atoms subject to an external magnetic field [1]. Such oscillations have subsequently been observed [2], and the determination of the concomitant oscillation frequency can be used to determine the ground state Ps hyperfine splitting (HFS), i.e., the energy difference between the singlet and triplet ground states [3, 4]. The main limitation of this approach is the need to determine the applied magnetic field to high precision, making it less precise than other methods used to determine the Ps HFS, for example, Zeeman splitting measurements [5, 6] or microwave spectroscopy [7]. Furthermore, all previous HFS measurements employing quantum oscillations have been performed using Ps atoms generated by positrons, from beta-plus decays, passing through a gas source, introducing uncertainties to the properties of the produced Ps atoms. Here we discuss the prospects for performing a beam-based measurement, where the produced Ps atoms will be of lower energies, on the order of 100 meV, in a well-defined volume, and, hence, in a well-characterized magnetic field. Specifically, we present simulations of the modulated Ps decay spectra under various experimental conditions, and identify the extent to which different systematics are likely to impact a determination of the Ps HFS under these conditions.

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Environmental effects in precision measurement: control or rather compensate

György Szondy [1]

[1]1. Department of Geodesy and Surveying, Faculty of Civil Engineering,
Budapest University of Technology and Economics, Műegyetem rkp. 3., H-1111 Budapest, Hungary
†corresponding author's email: szondy.gyorgy@emk.bme.hu

The fundamental precondition of General Relativity is the equivalence of gravitational and inertial mass (Weak Equivalence Principle - WEP). It was suggested by Fischbach et al. only in 1986 - based on the results of torsion balance measurements made by Eötvös et al. in 1906-1908 - that the equivalence principle might be violated. We – the BME-Wigner Experimental Gravity Group – want to find an explanation of the apparent violation by modernizing a precision Eötvös torsion balance and repeating the original experiment with much higher precision.

However, with a resolution increased by 3 orders of magnitude, environmental perturbations (p, T, tilt, seismic and human noise) of the instrument became crucial. Therefore, to be able to compensate them, in the present study I measured and analyzed some of these effects mainly using a Lippmann nrad resolution tiltmeter.

In my study I describe the common error in the temperature measurement practice and the method to increase the resolution by 1-2 orders of magnitude. Moreover, I show the effect of atmospheric pressure change on the operating temperature of the instrument, and describe its mechanism.

I found that in general, pressure changes have, well-measurable effect on instrument temperatures through adiabatic temperature changes and through the effect of so-called self-heating. More importantly, as the control of environmental parameters (p, T) generates at least 2-3 orders of magnitude greater noise than the effects under study, so these kind of high precision results cannot be obtained with active control of environmental parameters, only with the approach of isolation and compensation.

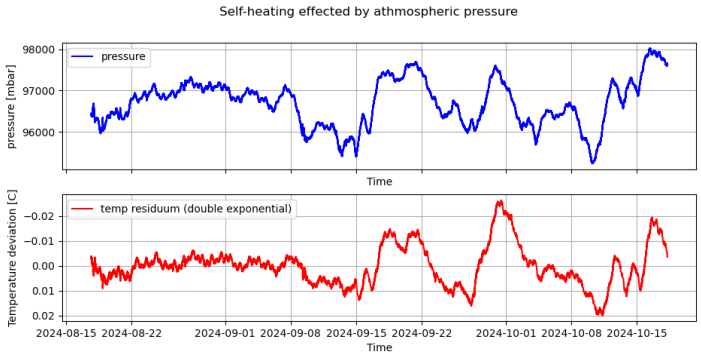

Figure 1: The slight effect of atmospheric pressure change on instrument temperature can be measured and considered.

Acknowledgments

I'd like to thank to the BME-Wigner Experimental Gravity Group and especially dr. Gyula Tóth for his crucial professional work in the Eötvös project, Gábor Papp for supporing the tilt-meter measurements. as well as Prof. Dr. Lajos Völgyesi and dr. Péter Ván for their comments and feedbacks.

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Enhanced antihydrogen accumulation with laser-cooled Be^+

Joanna Peszka[1,2], **ALPHA Collaboration**

[1]Department of Physics, Faculty of Science and Engineering, Swansea University, Swansea, UK
[2] TBA

The study of cold antihydrogen for CPT symmetry tests began in 2010 with the first successful demonstration of trapping individual antihydrogen atoms [1]. In the ALPHA experiment, antihydrogen is produced via a three-body recombination process involving one antiproton and two positrons [2]. Antihydrogen is formed by combining cold plasmas of positrons and antiprotons in a specialized Penning-Malmberg trap, which spatially overlaps with a magnetic minimum trap designed to confine antihydrogen atoms [3]. Due to the shallow depth of the magnetic potential - capable of trapping only atoms with kinetic energies corresponding to temperatures below 0.5 K - early experiments typically confined ~20 antihydrogen atoms per production cycle. In 2017 the technique was advanced to allow continuous synthesis and accumulation of antihydrogen [4, 5], enabling key milestones such as the first high-precision measurement of the 1S–2S transition [6] and the first observation of gravity's influence on antimatter [7].

Antihydrogen production through the three-body recombination process depends on the thermal energy of the positrons; both the production and trapping rates increase as the positron temperature decreases. So far the temperature of positron plasma in ALPHA-2 trap was limited to around 20K, which was achieved via the cyclotron cooling mechanism in the high magnetic field. To reduce the temperature of the positron plasma even further, an active cooling mechanism is required.

Inspired by pioneering work at NIST [8], a sympathetic cooling of positrons with laser-cooled beryllium ions (Be^+) was proposed [9]. The Be^+ ions are generated via laser ablation of a solid beryllium target [10], then confined within a Penning-Malmberg trap and Doppler cooled using a 313 nm laser. Upon merging with the positron plasma, the laser-cooled Be^+ ions carry away thermal energy from the positrons through Coulomb interactions. Sympathetic cooling technique allowed to achieve ~2.5 times lower temperatures of positron plasma than before [11].

Early development of Be^+ laser-cooling technique suffered from irreproducibility of the number of ablated beryllium ions and inefficient laser-cooling scheme. Several laser system upgrades were performed, most importantly to allow for simultaneous laser-cooling and Be^+ cloud compression using Rotating Wall technique [12]. This improved laser-cooling technique was successfully integrated into the standard antihydrogen synthesis cycle. An eight-fold enhancement in antihydrogen trapping efficiency per synthesis cycle has been demonstrated, enabling the accumulation of over 15,000 antihydrogen atoms in less than seven hours.

The implementation of sympathetic cooling of positrons method into antihydrogen production cycle has not only accelerated the experimental timeline but also opened new opportunities for detailed investigations of fundamental symmetries. These include potential searches for sidereal variations and other precision tests of antimatter and its interactions, which were previously inaccessible due to limited sample sizes and extended accumulation times.

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Development of new superfluid helium-based muonium sources for the LEMING experiment

A. Antognini[1,2], M. Bartkowiak[2], E. Dourassova[1], R. Gartner[1], D. Goeldi[1], K. Jefimovs[2], A. Knecht[2], K. Kirch[1,2], F. Lancellotti[1], C. Regenfus[1], R. Scheuermann[2], A. Soter[1,*], D. Taqqu[2], R. Waddy[1], F. Wauters[3], P. Wegmann[1], J. Zhang[1]

[1]Institute for Particle Physics and Astrophysics, ETH Zürich, 8093 Zürich, Switzerland
[2]Paul Scherrer Institut, 5232 Villigen-PSI, Switzerland
[3]Johannes Gutenberg University of Mainz, 55122 Mainz, Germany
[*] Email: asoter@phys.ethz.ch

The LEMING experiment aims to measure the gravitational acceleration of muonium (Mu = $\mu^+ + e^-$), a purely leptonic, exotic atom. Mu provides the only viable system to directly test the Weak Equivalence Principle on second generation anti-leptons. It also allows probing the coupling of gravity to the muon mass - a fundamental parameter of the Standard Model - without significant contributions from the strong interaction. The experiment utilizes an atom interferometer, which requires a novel coherent vacuum muonium source.

We have developed such a source by stopping a conventional muon beam in a superfluid helium (SFHe) target. Mu atoms are efficiently emitted from bulk SFHe as a beam with low angular divergence and a narrow velocity distribution. These properties continue to be investigated, particularly in the interest of developing an optimized vertical SFHe target. This new target employs a finely structured silicon grating, which traps SFHe within micron-sized trenches via capillary action. By directly generating a horizontal atomic beam, this novel microfluidic target removes the need for a beam reflector, significantly reducing decay losses caused by the short lifetime of the atoms ($\tau_{Mu} = 2.2\,\mu s$).

In this contribution, we present recent measurements demonstrating the emission of Mu from microfluidic targets of various sizes. We discuss the technical aspects of optimizing and integrating such a target into our current interferometer prototype. Additionally, an upgrade of the cryogenic detection system to silicon strip tracking detectors is presented.

Updates from the Hydrogen 1S-3S Direct Frequency Comb Spectroscopy Experiment at MPQ

Vincent Weis [1, †], **Derya Taray** [1], **Vitaly Wirthl** [1], **Omer Amit** [1], **Thomas Udem** [1,2], **Theodor W. Hänsch** [1,2]

[1]Max Planck Institute of Quantum Optics, Garching, Germany
[2]Department of Phyiscs, LMU, Munich, Germany
†corresponding author's email: vincent.weis@mpq.mpg.de

Due to its simple structure, the Hydrogen atom is a powerful platform for precision tests of fundamental physics, more explicitly quantum electrodynamics. The energy levels in atomic Hydrogen can be calculated up to a high degree of precision and can be written as:

$$E_{n,l,j} = hc\mathbf{R_y}\left(-\frac{1}{n^2} + f_{n,l,j}(\alpha, \frac{m_e}{m_p}, ...) + \delta_{l,0}\frac{C_{NS}}{n^3}\mathbf{r_p}^2\right), \tag{1}$$

where $f_{n,l,j}$ is the QED series expansion in the fine structure constant α, containing various corrections to the leading Bohr-level term. The last term describes the contribution due to the finite size effect, i.e. the fact, that the proton in the atom core is not a point-like particle but has a charge distribution with the RMS charge radius r_p to which the s-states ($l = 0$) are sensitive to, due to their finite spatial overlap of the wave function with the atom core. As other required parameters, such as α or the electron to proton mass ratio m_e/m_p can be determined very accurately by other experiments in atom interferometers and Penning traps, R_y and r_p remain to be ascertained by spectroscopy [3]. Thus, two transition measurements in hydrogen are required to fix R_y and r_p and more to check for consistency. Contributing to that quest, the 1S-3S experiment at MPQ in Garching delivered its first result in 2020 with a fractional uncertainty of 10^{-13} [2]. The 1S-3S transition was also measured by colleagues at the Laboratoire Kastler Brossel in Paris [1], with a value different to the MPQ measurement by 2.1 standard deviation. Thus, this experiment is of particular importance as it provides the only transition measurement in Hydrogen that has been conducted redundantly by two groups with independent systematics and modern laser spectroscopy techniques. Strongly hinting to unknown experimental issues, this discrepancy motivates the further improvement of the experimental setup towards a lower uncertainty measurement. In this poster, an overview of the experimental setup is given, together with an outlook on the improvements expected from modifications currently underway.

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From a molecular tritium source at the Karlsruhe Tritium Neutrino Experiment (KATRIN) and to an atomic tritium source for KATRIN++

Magnus Schlösser [1, †] **for the KATRIN collaboration**

[1]Tritium Laboratory Karlsruhe, Institute of Astroparticle Physics, Karlsruhe Institute of Technology,
Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany
†corresponding author's email: magnus.schloesser@kit.edu

The Karlsruhe Tritium Neutrino (KATRIN) experiment determines the neutrino mass from the electron spectrum of the tritium beta-decay. Recently, it has improved the upper bound on the incoherent sum of neutrino masses down to $m_\beta < 0.45$ eV (90% C.L.), with its full data set, acquired by then end of 2025, targeting a final sensitivity of < 0.3 eV. To further improve this sensitivity down to the 0.05 eV level, which allows cross-validation of the other mass measurement approaches, and answer the question of normal or inverted neutrino mass ordering, fundamentally new technological developments are necessary.

The state-of-the-art KATRIN experiment employs a molecular tritium source, operating at approximately 10^{11} beta decays per second, alongside an integration filter possessing a filter width of $\Delta E = 2.7$ eV. Reaching down to inverted ordering with such a "KATRIN-like" configuration would necessitate either a significantly stronger source or a decades-long measurement program, both of which are impractical from a technical standpoint. Substantial improvement in neutrino-mass sensitivity could be realized by transitioning to a detection method employing high-resolution differential measurement techniques. However, such a differential method needs to achieve an energy resolution of well below 1 eV (FWHM). This approach would outperform the current integrating MAC-E filter by using statistics more efficiently, as the energy of individual electrons is measured.

Current research and development efforts in the KATRIN context focus on (i) time-of-flight measurements and (ii) large arrays of quantum sensors.

To further enhance neutrino-mass sensitivity in future experiments, atomic tritium must replace the current molecular tritium-based β-electron source. The β-decay of molecular tritium, $T_2 \rightarrow {}^3HeT^+ + e^- + \overline{\nu}_e$, differs from that of atomic tritium, $T \rightarrow {}^3He^+ + e^- + \overline{\nu}_e$, primarily in the final state spectrum of the daughter molecular ion, ${}^3HeT^+$. Moreover, molecular tritium decay leaves only 57% of daughter molecules in the electronic ground state, while atomic tritium decay increases this fraction to 70% for daughter atoms, boosting the number of relevant decay electrons near the spectral endpoint.

Furthermore, ${}^3HeT^+$ remains in an excited ro-vibrational state, broadening the β-spectrum to approximately 1 eV (FWHM) and inherently limiting neutrino mass sensitivity, even with advanced detector resolutions. Unlike T_2, the fermionic ($s = 1/2$) tritium atom can be manipulated using inhomogeneous magnetic fields, enabling trapping and cooling below the freeze-out temperature of T_2 to minimize Doppler broadening of β-decay electrons.

For implementation in KATRIN++, atomic tritium will be needed in copious amounts – comparable to the current molecular source of KATRIN – to achieve the required statistics. For this purpose, a large-scale demonstration experiment needs to be set up with the following goals: (a) Generation of large quantities of atomic tritium. (b) Development and implementation of effective atom cooling mechanisms. (c) Study of trapping times and maximum densities in a magnetic trap. (d) Investigation of the interplay of beta-driven plasma (meV-eV) and ultra-cold trapped atoms (neV).

We expect that the generation, cooling, and trapping of tritium atoms will suffer from low efficiencies in each step. Therefore, even for the demonstration experiment, macroscopic amounts of tritium must be used, which are estimated to be at the level of 10 g (T_2). This can only be done in a large-scale laboratory able to host and operate such a loop. The mission is to realize a global Atomic Tritium Pathfinder (ATP) at the Tritium Laboratory Karlsruhe (TLK). To achieve this, a joint working group is in the process of being formed. The partners for the ATP consortium will include those from various specialized areas: Neutrino mass partners such as KATRIN++, Project 8, and QTNM. In addition, partners from atomic and molecular physics, quantum gases, and precision spectroscopy are welcome to join this consortium.

This poster supplements the talk titled "Recent results from the Karlsruhe Tritium Neutrino Experiment (KATRIN) and the future atomic tritium source for KATRIN++" at the same conference.

The Excited Electronic States of the Helium Dimer Including Relativistic and Adiabatic Effects

Dawid Dąbrowski[1,*], **Marcin Gronowski**[1], **Michał Przybytek**[2], **Michał Tomza**[1,†]

[1]Faculty of Physics, University of Warsaw, ul. Pasteura 5, 02-093 Warszawa, Poland
[2]Faculty of Chemistry, University of Warsaw, ul. Pasteura 1, 02-093 Warszawa, Poland
[*]d.dabrowsk12@student.uw.edu.pl [†]michal.tomza@fuw.edu.pl

Background The helium dimer serves as an exemplary system for advancing our understanding of few-body physics, high-resolution laser spectroscopy, and the properties of ultracold molecules. The electronic structure of four-electron systems, like He_2, can be calculated with unparalleled accuracy. While previous *in silico* studies have attained a reasonable level of accuracy, they remain insufficient for reliably guiding and interpreting state-of-the-art experiments. The last high-accuracy calculation [1] deviates from the experimental results by approximately 1.5‰, which is still inadequate for making direct comparisons and providing meaningful insights for cutting-edge spectroscopic research. Highly accurate *ab initio* results not only allow for a direct comparison with experimental data but also guide upcoming experiments and pave the way towards the verification of the Standard Model.

Purpose This study aims to achieve benchmark-quality potential energy curves (PECs) with the highest possible accuracy for the few lowest excited states of the helium molecule. We systematically explore these states using various methods and basis sets to provide a reliable estimate of the accuracy of our computations. After incorporating relativistic and adiabatic corrections, we achieve an exceptional level of accuracy, which is essential for guiding ongoing experiments.

Method We utilize an extensive range of molecular electronic structure theory methods, including coupled cluster approaches (CCSD(T), CCSDT, EOM-CCSD, EOM-CC3) and configuration interaction (Full CI) methods. Our calculations employ basis sets developed for the He(^{1}S) + He(^{3}S) states with cardinal numbers up to 10Z, with results extrapolated to the complete basis set limit.

Results Potential energy curves (PECs) are calculated for interatomic distances up to 50 a_0. The states from the first four asymptotes are computed using the Full CI method with basis sets up to 7Z and various coupled cluster methods with basis sets up to 8Z. Additionally, a single-point calculation for the $a^3\Sigma_u^+$ and $c^3\Sigma_g^+$ states is provided in the 8Z basis set using Full CI, and in the 10Z basis set using EOM-CC3 to demonstrate convergence at the global minimum. Our calculations achieve a theoretical accuracy reaching **1.0 cm^{-1} (60-200 ppm)** at the minimum.

Conclusions The results of our calculations provide highly accurate data, enabling the calculation of Franck-Condon factors for higher Rydberg states of the helium dimer or the helium molecular ion [2]. We report that our study has achieved the highest accuracy for the helium dimer in excited electronic states.

Acknowledgments

Polish high-performance computing infrastructure PLGrid, grants no. PLG/2023/016878 & PLG/2024/017527.
European Research Council (ERC), grant no. QuantMol/101042989.
National Science Centre, Poland, grant no. 2020/38/E/ST2/00564.

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Measurement of geometric distance between silicon spheres with laser interferometry in determination of G

Yanjie Zhang [1], **Tong Huang** [1], **Ruiqi Liu** [1], **Qing Li** [1, †]

[1]National Gravitation Laboratory, MOE Key Laboratory of Fundamental Physical Quantities Measurement, and School of Physics, Huazhong University of Science and Technology, Wuhan 430074, People's Republic of China
†corresponding author's email: qingli@hust.edu.cn

The time-of-swing method and the angular acceleration feedback method were used in our last measurement of G in 2018, both of which gave the values of G with an uncertainty of 12 ppm. In the two methods, the distances between the geometric centers of the source masses are the main error sources. For example, in the time-of-swing method, a 0.36 μm uncertainty of geometric distance introduces 9.3 ppm to the G value. If the measurement precision of the geometric distance can be reduced to 0.1 μm, its contribution to the G value is less than 1 ppm, so that it is no longer the main error source in the experiment.

In the on-going G measurement, the silicon spheres with more uniform density will be used. The roundness of the silicon spheres is expected to be 0.1 μm. The laser interferometry is used to measure the geometric distances between the spheres, which is a non-contact measurement method, has a very high precision, and can be carried out on the site to improve the reliability of measurement result. So far, the apparatus of measuring the geometric distances has been built. The measurement principle is analyzed, and the error sources, such as the laser, the sphere, the alignment of optical path, and the environment are evaluated. The measurement uncertainties of the horizontal and vertical geometric distances reach 11 nm and 9 nm, respectively. In the next step, the silicon spheres will be processed with great care, and the on-going G measurement is expected to give a new result in a few years.

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A measurement of the $2S_{1/2}$ hyperfine interval in atomic hydrogen

Dylan C. Yost [1, †], **Ryan G. Bullis** [1], **Cory Rasor** [1], **William L. Tavis** [1], **Scott A. Johnson** [1], **Michael R. Weiss** [1]
†corresponding author's email: dylan.yost@colostate.edu

Department of Physics, Colorado State University, Fort Collins, Colorado, 80523, USA

The simple structure of the hydrogen atom allows for precise calculations that can be compared with experiment. The ground state hyperfine interval in atomic hydrogen has been measured extremely precisely. A comparison of the experimentally determined value with theory is limited by an insufficient understanding of proton structure effects. However, a linear combination of the $1S_{1/2}$ and $2S_{1/2}$ hyperfine intervals given by

$$D_{21} = 8\, f(2S_{1/2}) - f(1S_{1/2}), \tag{1}$$

largely eliminates the theoretical uncertainty in nuclear structure and is a stringent test of fourth-order bound-state QED [1]. A high-precision numerical calculation of the self-energy was performed in 2008, resulting in $D_{21}^{\text{Theory}} = 48\,954.1(2.3)$ Hz [2], which is the most up-to-date published value.

In addition to bound-state QED tests, several authors have noted that measurements of D_{21} can be used to provide constraints on light bosons with weak coupling to Standard Model particles [3, 4, 5]. Such hypothetical particles could manifest themselves by producing an additional spin-dependent interaction between the proton and electron, which would cause a deviation between the experimental and theoretical values of D_{21}.

We have recently completed a measurement of the $2S_{1/2}$ hyperfine interval, which when combined with precise measurements of the ground state hyperfine interval, provides a measure of D_{21} [6]. The measurement was done using Ramsey spectroscopy with a thermal beam cooled to cryogenic temperatures. The measured value is 177 556 838.87(85) Hz, which represents the most precise determination of this interval to date. Using the value of $f(2S_{1/2})$ from this work gives a value of $D_{21}^{\text{Exp}} = 48\,959.2(6.8)$ Hz, which is in agreement with the theoretical value of $D_{21}^{\text{Theory}} = 48\,954.1(2.3)$ Hz.

Acknowledgments

We gratefully acknowledge funding through a Center for Fundamental Physics grant from the John Templeton Foundation and Northwestern University, NSF Career Award #1654425, and NSF Award #2207298.

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Toward High-Precision XUV Spectroscopy of the 1S-2S Transition in He^+

Florian Egli [1, †], **Jorge Moreno** [1], **Johannes Weitenberg** [1,2], **Theodor W. Hänsch** [1,3], **Thomas Udem** [1,3], **Akira Ozawa** [1,4]

[1]Max-Planck-Insititut für Quanten Optik, Hans-Kopfermann-Straße 1, 85748 Garching, Germany
[2]Fraunhofer-Institut für Lasertechnik ILT, Steinbachstraße 15, 52074 Aachen, Germany
[3]Fakultät für Physik, Ludwig-Maximilians-Universität München, Schellingstraße 4, 80799 Munich, Germany
[4]Institute for Multidisciplinary Sciences, Yokohama National Univeristy, 79-5 Tokiwadai, Hodogaya Ward, Yokohama City, 240-8501 Kanagawa, Japan
†corresponding author's email: florian.egli@mpq.mpg.de

Bound-state quantum electrodynamics (QED) accurately describes the energy levels of hydrogen-like atoms and ions. High-precision laser spectroscopy experiments provide one of the best tests of the theory. The frequency of the narrow 1S-2S transition of atomic hydrogen has been measured with a relative uncertainty of less than 10^{-14}. By combining two spectroscopic measurements of a hydrogen-like system, the Rydberg constant and the nuclear charge radius can be determined. The comparison of physical constants obtained from different measurement combinations serves as a consistency check for the theory [1]. It is valuable to study different hydrogen-like systems, as they exhibit varying sensitivities to different contributions of the theory. The measurement of the Lamb shift in muonic hydrogen, for instance, has enhanced sensitivity to the proton radius and led to the proton radius puzzle [2].

Another interesting spectroscopic target is the hydrogen-like He^+ ion. Higher-order QED corrections scale with high powers of the nuclear charge, making He^+ significantly more sensitive to these effects than hydrogen. We are preparing an experiment to measure the 1S-2S two-photon transition in He^+ [3]. Ideal conditions for high-precision measurements are achieved by holding a small number of He^+ ions nearly motionless in the field-free environment of a Paul trap, where they are sympathetically cooled by co-trapped Be^+ ions. The 1S-2S transition will be excited by an extreme-ultraviolet (XUV) frequency comb at 60.8 nm, generated via high-harmonic generation from a high-power infrared frequency comb. After successful excitation to the 2S state, a significant fraction of the He^+ ions will be further ionized to He^{2+} and remain in the Paul trap. Sensitive in-situ mass spectrometry using secular excitation will detect the number of trapped He^{2+} ions, serving as a single-event-sensitive spectroscopy signal.

To perform Doppler-free spectroscopy of the He^+ transition, two counterpropagating pulses of the frequency comb must overlap spatially and temporally at the ion position. Achieving this overlap before the spectroscopy experiment is crucial to find the spectroscopy signal within a reasonable measurement time, making it a critical preparatory milestone. Another key milestone is the installation of a custom XUV spectrometer to fine-tune the spectral envelope of the frequency comb to match the expected He^+ transition.

This poster provides an update on the progress toward He^+ spectroscopy in our experiment and offers an opportunity to further discuss the details presented in the accompanying talk.

Acknowledgments

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (Grant Agreement No. 742247). T. W. Hänsch acknowledges support from the Max-Planck Foundation.

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Bounds on a fifth force from hydrogen, deuterium and helium spectroscopy

Matthew Jones [1], **Adair Nicolson** [1,2], **Robert Potvliege** [1, †], **Michael Spannowsky**[3]

[1]Physics Department, Durham University, South Road, Durham DH1 3LE, UK
[2]Chemistry Department, University College London, Gower Street, London WC1E 6BT, UK
[3]Physics Department, Institute of Particle Physics Phenomenology, Durham University, South Road, Durham DH1 3LE, UK
†corresponding author's email: r.m.potvliege@durham.ac.uk

It has been recognised for some time that stringent bounds on the strength of a fifth force are set by high precision spectroscopy of hydrogen and deuterium [1–5]. We have revisited and continued these earlier investigations in the light of recent experimental and theoretical advances in the spectroscopy of hydrogen, deuterium, helium-3 and helium-4 and their muonic counterparts [6, 7]. Our main results, which we present in this poster, are bounds on a fifth force interaction between an electron and either a proton or a neutron. We also discuss the potential offered by a future high-precision measurement of the $1s_{1/2} - 2s_{1/2}$ interval of $^4He^+$ [8] for setting bounds on the interaction of an electron with a deuteron. These results do not depend on specific assumptions on how the interaction would couple to a deuteron compared to a proton or would couple to an α particle compared to a helion. They depend on its coupling to a muon, but not in a significant way for carrier masses below 100 keV if one assumes that the strength of the interaction with a muon would be of a similar order of magnitude as the strength of the interaction with an electron.

Specifically we consider the wide class of models that can be described by an effective Yukawa-type interaction between the nucleus and the electron (or the muon for the muonic species). We parametrize the strength of this new physics (NP) interaction by the product of the respective coupling constants — $g_e g_p$ for the interaction between a proton and an electron or $g_e g_n$ for the interaction between a neutron and an electron. We find that it is possible to set bounds on $|g_e g_p|$ that are orders of magnitude more sensitive than those set using a single isotope only provided the interaction couples differently to the deuteron and proton. Further enhancements of these bounds by an order of magnitude or more would be made possible by extending the current isotope shift data to measurements of a transition between the 2s state and a Rydberg s-state with an experimental error of 100 Hz or better [4, 6]. In the mass region considered, the bounds on $g_e g_n$ based on the World spectroscopic data for hydrogen and deuterium tend to be more stringent than the bounds arising from the analysis of King plots nonlinearities, in the current state of development of the latter approach — see, e.g., Figure 1 and Refs. [4] and [7]. Measuring the isotope shift of the $1s_{1/2} - 3s_{1/2}$ interval in hydrogen and deuterium to a precision of ~ 1 kHz would provide a useful independent check of these bounds [6].

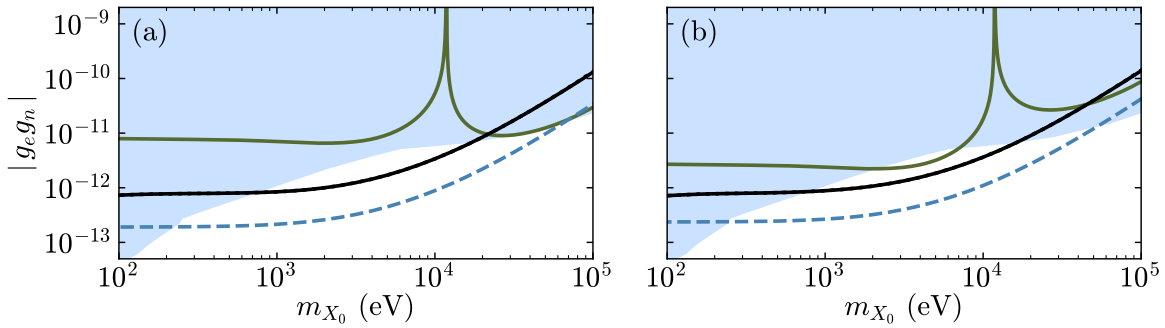

Figure 1: Bounds on $g_e g_n$, (a) for an attractive NP interaction, (b) for a repulsive NP interaction. Shaded area: region excluded by neutron scattering data combined with measurements of the anomalous magnetic moment of the electron [4]. Solid green curves: bounds derived from the Yb/Yb$^+$ isotope shift [9]. Solid black curves: bounds based on the World spectroscopic data for hydrogen and deuterium. Dashed curves: bounds based only on the $1s_{1/2} - 2s_{1/2}$ interval of eH, the isotope shift of the $1s_{1/2} - 2s_{1/2}$ interval and the μH and μD Lamb shifts. Adapted from Ref. [7].

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Calculation of the total 10th order QED contribution to the electron magnetic moment

Sergey Volkov [1, †]

[1] Max Planck Institute for Nuclear Physics, Saupfercheckweg 1, D 69117 Heidelberg, Germany
†corresponding author's email: sergey.volkov.1811@gmail.com

The author's calculation [1] of the 5-loop universal QED contribution to the electron anomalous magnetic moment is described on a *poster*. The following topics are covered:

- the necessity of this calculation for QED checking at the current level of experimental accuracy;
- the relationship with the values presented by T. Aoyama, M. Hayakawa, T. Kinoshita, M. Nio (it is the only team except the author who calculated this value);
- the results in detail;
- the method of calculation;
- realization and technical parameters.

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