International Conference on Precision Physics and Fundamental Physical Constants (FFK-2019)

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Balaton Limnological Research Institute of the Hungarian Academy of Sciences

Book of Abstracts

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Session 1: Precision spectroscopy of atoms and ions / 24

Calculation of higher order corrections to positronium energy levels

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I report on progress in the calculation of corrections to positronium energy levels of order $m\alpha^7$. Corrections at this level will be needed for the interpretation of the results of upcoming measurements. A procedure for the calculation of high order corrections has been developed based on the Bethe-Salpeter equation of dimensionally regularized NRQED and the method of regions. I demonstrate the effectiveness of this approach by using it to obtain all pure recoil corrections to positronium energies at $O(m\alpha^6)$ in a unified manner.

Session 2: High energy physics: experiment / 12

High-precision tests of the Standard Model at future e+e- colliders

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Perspectives of high-precision tests of the Standard Model at future linear and circular electron-positron colliders are discussed. The physical programs of future high-energy e+e- colliders are briefly described. Challenges in providing theoretical predictions with the required accuracy are pointed out. Recent results of the SANC group on electroweak radiative corrections to Bhabha scattering and several annihilation channels are presented. Order $\alpha^3 L^2$ contributions to QED collinear radiator factors are calculated.

Poster session / 68

Nonrelativistic ionization energy levels of the helium atom

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The nonrelativistic ionization energy levels of a helium atom are calculated for S, P, D and F states. The calculations are based on the variational method of "exponential" expansion. The convergence of the calculated energy levels is studied as a function of the number of basis functions N. This allows us to claim that the obtained energy values (including the values for the states with a nonzero angular momentum) are accurate up to 28-35 significant digits.

[1] C. Schwartz, Experiment and theory in computations of the He atom ground state. Int. J. Mod. Phys.E 15, 877 (2006); C. Schwartz, Further Computations of the He atom ground state. ArXiv:math-phys/0605018, (2006).
[2] V.I. Korobov, Nonrelativistic ionization energy for the helium ground state. Phys.Rev. A 66, 024501 (2002).
[3] V.I. Korobov, Coulomb three-body bound-state problem: variational calculations of nonrelatistic energies. Phys. Rev.A. 61, 064503 (2000).

Poster session / 66

Quadropole transitions of the hydrogen molecular ion HD+

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Session 2: High energy physics: experiment / 20

CP Violation and CKM Matrix Measurements

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Do we fully understand basic constituents of the Universe and interactions between them? Is the way we describe within the Standard Model (SM) elementary particles and forces correct and complete? Are there any new particles beyond the SM?
Precise determination of elements of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix and measurements of the charge-parity (CP) symmetry violation comprise a central goal of flavour physics. Such precision studies of the SM flavour structure allow probing indirect effects of new particles, including those being too heavy to be produced directly even at colliders such as the LHC.
In this talk I will discuss the most important beauty and charm measurements that have paved the way for testing and challenging the SM predictions. The most precise results come these days from the LHCb experiment and are being greatly complemented with ones from B-Factories.

Session 10: Gravity, new measurements / 9

Determination of G with Angular-Acceleration-Feedback Method (material included in the preceding talk)

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Determination of G with Angular-Acceleration-Feedback Method

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The Newtonian gravitational constant G, which plays an significant role in many fields, is the first fundamental physics constant introduced by human beings, but the accuracy of G is the worst among all of the constant. In 2016, the Committee on Data for Science and Technology recommended an updated value of G(CODATA-2014) with a relative uncertainty of 47 ppm, which is still many orders of magnitude larger than that of other fundamental constants. Therefore, two independent determinations using torsion pendulum with the time-of-swing(ToS) method and the angular-acceleration-feedback(AAF) method were performed in the cave laboratory at Huazhong University of Science and Technology. This report will mainly focus on the latter. Compared with the previous precise torsion balance experiments, this method is extremely insensitive to the anelasticity of the fibre. Since 2008, the proof-of-principle experiments with AAF method have been carried out. Based on the preliminary results, a series of improvements were adopted to reduce sources of uncertainty in the present work. Meanwhile, we measured the G values at three different conditions, named as AAF-I, AAF-II and AAF-III. Finally, we obtained the weighted mean value of G for the AAF method is 6.674484(78)×10−11 m3 kg−1 s−2 with a combined relative uncertainty of 11.61 ppm.

Session 5: Beyond the Standard Model / 16

Towards testing physics beyond the Standard Model with the g factor of bound electrons

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We demonstrate the relevance of the g factor of bound electrons in few-electron ions to the search for physics beyond the Standard Model (SM). The contribution to the g factor from hypothetical forces beyond the SM can be calculated and, when compared to existing and potential experimental data, used to derive competitive bounds on the parameters of these forces.

A first method to implement this program consists in comparing the best available theoretical and experimental results, including data on the weighted difference of g factors of different electronic levels [V.A. Yerokhin et al., Phys. Rev. Lett. 116, 100801 (2016)]. Stringent bounds can be obtained in the future with this method, through the ongoing advancement of bound-state QED calculations at the two-loop level.

Another method makes use of the isotope shift. Inspired by a recent proposal concerning optical frequencies in ions [J.C. Berengut \textit{et al., Phys. Rev. Lett. 120, 091801 (2018)], we propose to use precision spectroscopy of the isotope shifts in the g factor of few-electron ions, to obtain bounds on a hypothetical fifth fundamental force. This method is based on experimental King plots, which are built from isotope shift data. By carefully considering subleading nuclear corrections to the g factor, our treatment allows for the precise interpretation of King plots. Plans to measure isotope shifts in g factors of highly charged ions with very-high precision [S. Sturm et al., Eur. Phys. J. Special Topics 227, 1425 (2019).] make our investigation especially timely.

Poster session / 21

Two-loop QED corrections to the bound-electron g factor involving the magnetic loop

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The g factor of bound electrons in light and medium-light hydrogen-like ions (e.g. C, Si) has been measured with an accuracy of a few parts in 10^{11} [S. Sturm et al., Nature 506, 467 (2014)]. Experiments such as ALPHATRAP and HITRAP aim at reaching this accuracy with heavy, few-electron ions, motivating the evaluation of two-loop radiative corrections.

We calculate a specific set of two-loop corrections to the bound-electron g factor in the hydrogen-like ground state. Diagrams belonging to this set include the magnetic loop as a subprocess and vanish in the free-loop approximation [V.A. Yerokhin and Z. Harman, Phys. Rev. A 88, 042502 (2013)]. At the lowest nonvanishing order, they involve the scattering of the external magnetic field in the Coulomb field of then ionic nucleus. We computed the electric-loop-magnetic-loop diagram, the magnetic-loop-after-loop diagram, and the self-energy-magnetic-loop diagrams, while also shedding light on some other diagrams, which feature a self-energy loop inside the magnetic loop. Our approach treats the binding of the electron to the nucleus nonperturbatively.

The computed corrections to the g factor are of order up to 10^{-7} in the case of ^{82}Pb. These corrections will be relevant to the projected determination of the fine-structure constant from g-factor measurements.

Session 4: QED tests on atoms and molecules / **48**

Hyperfine cross-over resonances producing Lamb-dips and Lamb-peaks in the saturation spectrum of HD

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Molecular hydrogen has evolved into a benchmark quantum test system for fundamental physics. Recent independent sub-Doppler determinations [1,2] of the weak dipole R(1) transition in the (2,0) overtone band of HD at λ~1.38 μm yield a discrepancy of 900 kHz or 9σ in combined uncertainty. We present measurements using Noise-Immune Cavity-Enhanced Optical Heterodyne Molecular Spectroscopy (NICE-OHMS), where the laser is locked to a Cs absolute frequency standard via an optical frequency comb [1]. The obtained saturation spectrum is found to exhibit a composite and pressure-dependent line shape, involving a Lamb-dip and a Lamb-peak. We propose an explanation of this behavior based on the effects of crossover saturation resonances in the hyperfine structure, which is made quantitative with a density matrix calculation. We expect to resolve the outstanding discrepancy between [1] and [2], which will enable the comparison of the measured R(1) transition frequency with the latest theoretical calculations [3].

[1] F. M. J. Cozijn, P. Dupré, E. J. Salumbides, K. S. E. Eikema, and W. Ubachs, Phys. Rev. Lett. 120, 153002 (2018).
[2] L.-G. Tao, A.-W. Liu, K. Pachucki, J. Komasa, Y. R. Sun, J. Wang, and S.-M. Hu, Phys. Rev. Lett. 120, 153001 (2018).
[3] P. Czachorowski, M. Puchalski, J. Komasa, and K. Pachucki, Phys. Rev. A 98, 052506 (2018).

Session 6: Magnetic moment, g factor / 28

The ALPHATRAP g-factor experiment

Authors: Alexander Egl[1]; Ioanna Arapoglou[1]; Martin Höcker[1]; Tim Sailer[1]; Bingsheng Tu[1]; Andreas Weigel[1]; Robert Wolf[1]; Sven Sturm[1]; Klaus Blaum[1]

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The ALPHATRAP experiment [1] at the Max-Planck-Institut für Kernphysik is a cryogenic Penning-trap setup to perform high-precision g-factor measurements on highly charged ions (HCI) up to hydrogenlike $^{208}Pb^{81+}$, to test bound-state quantum electrodynamics (BS-QED) [2]. In the vicinity of the nucleus, the electrons bound in HCI experience the strongest electric and magnetic fields that can be found in a stable system in the laboratory, which allows for tests of BS-QED under extreme conditions. Furthermore also fundamental constants such as the electron atomic mass [3] or eventually the fine structure constant α can be determined from such systems.
For the measurement of the bound electrons g-factor a cryogenic double Penning-trap setup is used which enables sub-parts-per-billion precision. It has the capability to capture and store HCI that are produced externally in designated ion sources and injected via a room-temperature beamline. Among the ion sources is the Heidelberg electron beam ion trap (HD-EBIT) which is designed to produce even the heaviest HCI or a laser ablation source for the production of singly-charged Be^{+} ions for an envisaged use in sympathetic laser cooling scheme for HCI. The trapped ion's eigenfrequencies can be determined with ultra-high precision in a highly homogeneous magnetic field of the compensated and orthogonal 7-electrode precision trap that allows mitigating inharmonic higher order electric field components. The spin-related magnetic substate of the electron can be detected non-destructively in the analysis trap by making use of the continuous Stern-Gerlach effect which enables spectroscopy of the Larmor precession frequency.
We will present the status of the ALPHATRAP experiment as well as report on recent results on the first measurement of the ground state magnetic moment (g-factor) in a single boronlike $^{40}Ar^{13+}$ with precision of a few parts per billion [4] and laser spectroscopy of an electric-dipole-forbidden fine structure transition ($2^2P_{1/2}$–$2P_{3/2}$) in $^{40}Ar^{13+}$, using a novel method which does not rely on any fluorescence signal and that opens up the possibility for further high-precision BS-QED tests.

[1] S. Sturm, et al., The European Physical Journal Special Topics 227.13, 1425-1491 (2019)
[2] S. Sturm, et al., Phys. Rev. Lett. 107.2, 023002 (2011)
[3] S. Sturm, et al., Nature 506.7489, 467 (2014)
[4] Arapoglou et al., accepted for publication in Phys. Rev. Lett.

Session 3: Exotic atoms / 46

Hyperfine Splitting in Muonium: Theory meets Experiment

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Theory of hyperfine splitting in muonium and perspectives of its improvement will be reviewed. Emphasis will be on the controversial estimate accuracy of the theoretical prediction. Comparison between theory and the existing and future experimental data will be discussed.

Session 6: Magnetic moment, g factor / 77

e+e- annihilation into hadrons and muon g-2

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We discuss precise measurements of exclusive and inclusive cross sections performed at various e+e- colliders in the BaBar, BESIII, CMD-3, KEDR, KLOE and SND experiments. Results of these measurements are used for the calculation of hadronic vacuum polarization - an important ingredient of the theoretical prediction for the muon $g-2$ and running fine structure constant in the Standard Model.

Session 8: The gravity experiment of Roland Eötvös / 17

My time with Bob Dicke; the beginning of experimental gravitational physics in university research

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In the Fall of 1955, Bob Dicke, returned to Princeton from his Sabbatical at Harvard and brought with him the thought that the experimental basis of general relativity was thin and that much more was needed including a modern high precision version of the Eötvös experiment. To this end, he established a program of carrying out high-precision gravitational experiments at Princeton. The bulk of my talk will be about this period and my good fortune and experiences working in Bob's group at that time. The talk will also have a prelude and a postlude in which I will discuss other, but related, scientific experiments and issues.

Session 8: The gravity experiment of Roland Eötvös / 61

The Enduring Significance of Eötvös' Most Famous Experiment

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Poster session / 29

Relativstic corrections to the hyperfine structure of hydrogen molecular ions

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Recent advances of Doppler-free rovibrational spectroscopy of HD+ ions [1,2] underline the high potential of these systems for accurate tests of molecular theory and determination of fundamental constants. However, analysis of experimental data is made more complex by the hyperfine structure. Measurement of a sufficient number of hyperfine components is required in order to extract a spin-averaged rovibrational transition frequency [3], which can then be accurately compared to the theory [4]. In practice, this may be difficult to achieve due to technical reasons [1,2], and one then has to use the theoretical determination of hyperfine shifts to extract the spin-averaged transition frequency. In Ref [1] the comparison between theory and experiment was limited by the HD+ hyperfine structure theory.

In this poster we will describe our calculations of relativistic corrections to the hyperfine structure of HD+ and H2+, especially to the spin-orbit and spin-spin tensor interactions. The complete effective Hamiltonian at orders m alphaˆ6 and m alphaˆ6 (m/M) is derived in the NRQED framework. Induced corrections are then calculated by applying the nonrelativstic perturbation theory, using three-body variational wavefunctions. Comparisons are made with experimental data whenever available.

[1] S. Alighanbari et al., Nature Phys. 14, 555 (2018).
[2] J.-Ph. Karr et al., J. Phys. : Conf. Ser. 723, 012048 (2016).
[3] S. Schiller, V.I. Korobov, Phys. Rev. A 98, 022511 (2018).
[4] V.I. Korobov, L. Hilico, J.-Ph. Karr, Phys. Rev. Lett. 118, 233001 (2017).

Poster session / 5

Diatomic Molecules as Probes for Nuclear Anapole Moment Effect

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Co-authors: Miroslav Iliaš ; Anastasia Borschevsky

The nuclear anapole moment can be used to test low-energy quantum chromodynamics and parity nonconservation in nuclei. Diatomic molecules possess rich and varied spectra and nearly degenerate energy levels, which provide strong enhancements for nuclear anapole moment effects, making it possible to search for new physics beyond the standard model in a small experiment. In order to extract the magnitude of nuclear anapole moment from measurements, a P-odd interaction coefficient WA, which depend on molecular structure, needs to be calculated with high accuracy. In this presentation, the measurement principle is briefly introduced and the WA coefficients calculated within different methods for some diatomic molecules of interest are presented and discussed.

Session 6: Magnetic moment, g factor / 33

Theory of the g factor of few-electron ions

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Quantum electrodynamic (QED) effects in strong Coulomb fields have been scrutinized recently in high-precision Penning trap g factor experiments. The uncertainty of the atomic mass of the electron has been largely decreased via measurements with the hydrogenlike $^{12}C^{5+}$ ion, and by using the theoretical value of the g factor. In order to further reduce uncertainties in the theoretical description, we calculate further higher-order corrections, such as two-loop Feynman diagrams in nonperturbative nuclear fields [1-3].

In future, an independent determination of the fine-structure constant α may also be possible by employing a specific weighted difference of the g factors of the hydrogen- and lithiumlike (or, alternatively, boronlike) ions of the same element. This weighted difference in chosen to cancel uncertainties due to nuclear effects. It is shown that this method can be used to extract a value for α from bound-electron g-factor experiments with an accuracy competitive with or better than the present literature value [4,5]. In a very recent experiment, the g factor of the boronlike $^{40}Ar^{13+}$ ion has been measured with an uncertainty on the 10^{-9} level, in agreement with the most recent theoretical predictions [6]. This represents a significant step towards the determination of α from the bound-electron g factor.

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[2] V. A. Yerokhin, Z. Harman, Phys. Rev. A **88** (2013) 042502.
[3] V. Debierre, B. Sikora, H. Cakir, N. S. Oreshkina, Z. Harman, C. H. Keitel, to be published.
[4] V. A. Yerokhin, E. Berseneva, Z. Harman, I. I. Tupitsyn, C. H. Keitel, Phys. Rev. Lett. **116** (2016) 100801.
[5] V. M. Shabaev, D. A. Glazov, N. S. Oreshkina, A. V. Volotka, G. Plunien, H.-J. Kluge, and W. Quint, Phys. Rev. Lett. **96** (2006) 253002.
[6] I. Arapoglou, A. Egl, M. Hocker, T. Sailer, B. Tu, A. Weigel, R. Wolf, H. Cakir, V. A. Yerokhin, N. S. Oreshkina, V. A. Agababaev, A. V. Volotka, D. V. Zinenko, D. A. Glazov, Z. Harman, C. H. Keitel, S. Sturm, and K. Blaum, Phys. Rev. Lett., in print (2019).

Session 7: Fundamental constants, atomic properties / 14

The hydrogen n=2 Lamb shift (and the proton size) and helium n=2 fine structure (and the fine-structure constant)

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We report on new measurements of the n=2 Lamb shift in atomic hydrogen using the new frequency-offset separated-oscillatory-fields (FOSOF) technique. This measurement can be used to determine the proton rms charge radius, and therefore contributes to the resolution of the proton size problem. A measurement of the J=1 to J=2 n=2 triplet-P fine structure interval is measured with unprecedented accuracy, again using the FOSOF technique. This interval, along with a similar measurement of the J=0 to J=1 interval (which we are presently performing) and along with sufficiently precise QED theory will allow for a precise determination of the fine-structure constant.

Poster session / 65

The hydrogen n=2 Lamb shift (and the proton size) and helium n=2 fine structure (and the fine-structure constant)

Author: Eric Hessels[1]

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Session 4: QED tests on atoms and molecules / 7

Determination of the dissociation energy of para-H2

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Determination of the dissociation energy of para-H2

J. Hussels, C.-F.Cheng, K.S.E. Eikema, E.J. Salumbides, W. Ubachs, Department of Physics and Astronomy, VU Amsterdam; N.J. Hölsch, M. Beyer, F. Merkt, Laboratorium für Physikalische Chemie, ETH Zurich; S.-M. Hu, Hefei National Laboratory for Physical Science at the Microscale, USTC, C. Jungen, UCL, London

The dissociation energy (D0) of H2 is an excellent benchmark quantity in quantum chemistry, with recent QED calculations now approaching accuracies achievable in simple atoms. New precision measurements of the GK-X molecular transition, in combination with other precision measurements, recently provided a value for D0 in ortho-H2. [1] The GK-state is populated from the X-state through Doppler-free two-photon spectroscopy using 179-nm radiation, generated by frequency upconversion using a BBO crystal and a KBBF crystal. The laser pulses at the fundamental wavelength are generated in a seeded, chirp-compensated, Ti:Sa oscillator-amplifier system where the seed is a narrowband Ti:Sa laser at 716 nm locked to a frequency comb. This enables sub-MHz level of accuracy for the GK-X energy splitting. In combination with CW-laser excitation of GK-np [2], millimeter wave transitions of inter-Rydberg transitions and extrapolation to the ionization limit, accurate values of the ionization limit and D0 of ortho-H2 were determined, the latter to 10−9 accuracy [1]. Here, additional work will be reported on para-H2, where the dissociation energy of the true ground state in the H2 molecule is determined. The difference of these two results gives the energy difference between the ground rovibronic states of ortho- and para-H2. The comparison of these accurate experimental results with improved calculations [3] may be interpreted to test the Standard Model of Physics [4].

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[2] M. Beyer, N. Hölsch, J. A. Agner, J. Deiglmayr, H.Schmutz, and F. Merkt,Phys. Rev. A97, 012501 (2018).
[3] M. Puchalski, J. Komasa, P. Czachorowski and K. Pachucki, Phys. Rev. Lett. 122, 103003 (2019)
[4] W. Ubachs, J.C.J. Koelemeij, K.S.E. Eikema and E.J. Salumbides, J. Mol. Spectr. 320, 1-12 (2016)

Poster session / 27

Two-photon spectroscopy of H2+

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The molecular hydrogen ion H2+ is a promising candidate for fundamental metrology. Measuring one or several rovibrational transition frequencies at the few-10-12 accuracy level would provide an independent measurement of the proton-to-electron mass ratio mp/me and may shed light on the proton radius puzzle [1].
This poster will report on recent progress towards this goal. We aim at measuring the (v=0,L=2) -> (v' =1,L'=2) transition Doppler-free two-photon transition at lambda = 9.17 µm. H2+ ions are stored in

a linear ion trap and sympathetically cooled by laser-cooled Be+ ions. Experimental results of state-selective preparation of H2+ ions in the v=0 and v=1 states and a demonstration of our detection mechanism via photodissociation will be presented.

[1] J.-Ph. Karr, L. Hilico, J.C.J. Koelemeij, V.I. Korobov, Phys. Rev. A 94, 050501(R) (2016).

Session 1: Precision spectroscopy of atoms and ions / 26

Improving the hyperfine structure theory in hydrogen molecular ions

Authors: Mohammad Haidar[1]; Zhen-Xiang Zhong[2]; Vladimir I. Korobov[3]; Jean-Philippe Karr[1]

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The hydrogen molecular ions H2+ and HD+ are promising systems for fundamental constants metrology. Their spectrum offer many ultra-narrow ro-vibrational transitions, the frequencies of which are sensitive to the proton-electron mass ratio, proton charge radius, and Rydberg constant [1]. Several projects aiming at high-accuracy measurements using Doppler-free spectroscopy schemes [2-4] are in progress.
The interpretation of experimental data requires improved theoretical description of the hyperfine structure [4]. The leading terms of the hyperfine Hamiltonian, i.e. the spin-spin Fermi contact interactions, have been calculated with high precision [5], but the theoretical accuracy is limited by the spin-orbit and spin-spin tensor interactions, which have been so far evaluated in the framework of the Breit-Pauli Hamiltonian [6,7]. The calculation of higher-order relativistic corrections to these interaction terms, following the NRQED approach, will be presented.
[1] J.-Ph. Karr, L. Hilico, J.C.J. Koelemeij, V.I. Korobov, Phys. Rev. A 94, 050501(R) (2016).
[2] L. Hilico, N. Billy, B. Grémaud, D. Delande, J. Phys. B 34, 491 (2001).
[3] V.Q. Tran, J.-Ph. Karr, A. Douillet, J.C.J. Koelemeij, L. Hilico, Phys. Rev. A 88, 033421 (2013).
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Session 7: Fundamental constants, atomic properties / 22

New quantum SI units and fundamental constants

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The International system of units, SI, has just been changed once again. The new definitions, which concern the kilogram, ampere, kelvin, and mole, are to come in force on May, 20. Similarly to the definition of the metre in terms of the speed of light, those four units are now defined in the terms of adopted exact values of fundamental constants, such as the elementary charge, Planck, Boltzmann, and Avogadro constants.

I consider the new definitions and discuss how the four defining constants were measured for the last time. I discuss the advantages in the realization of the units and the methods to be applied for the new standards. I also consider what will change for the applications in particle, nuclear, and atomic physics.

Session 11: Miscellaneous / 84

Closing

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Session 7: Fundamental constants, atomic properties / 55

Study of the valence electronic density distribution in Z=112-120 atoms

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In the present report, localization properties of valence electronic density are studied for superheavy atoms in the range 112 ≤ Z ≤ 120. Atomic shell structure is revealed by means of electronic localization function in the Dirac-Fock approximation (ELF) [1]. Predictions for the radii and widths of the valence shells based on the ELF are compared with the radii and widths of the related Dirac-Fock orbitals. The data obtained for superheavy atoms with 112 ≤ Z ≤ 120 are compared with the corresponding results for atoms with 30 ≤ Z ≤ 38 and 80 ≤ Z ≤ 88. The influence of the relativistic effects on the distribution of the valence electronic density is estimated by performing the related calculations in the non-relativistic limit.

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Session 4: QED tests on atoms and molecules / 50

Energy levels of deuterium molecule

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Co-authors: Mariusz Puchalski [1]; Paweł Czachorowski [2]; Krzysztof Pachucki [2]

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Theoretical energy separation (ionization, dissociation, transition energy) is composed of several additive components. The total energy and its components for a light molecule can be well described in the framework of the nonrelativistic quantum electrodynamic theory (NRQED) [1] by the expansion in powers of the fine structure constant. The higher accuracy is expected, the more components must be involved. Furthermore, the higher accuracy is expected, the more accurate the involved components must be. In particular, the leading term of the expansion, which represents the nonrelativistic energy, is by far the dominating one and its accuracy can directly limit the accuracy of the total energy $E(\alpha)$. For example, attaining the 1 MHz ($\sim 3 \cdot 10^{-5}$ cm^{-1}) accuracy for the dissociation energy of D_2 requires 10 significant figures of the nonrelativistic component to be known. A common procedure of decomposing the nonrelativistic energy into the clamped nuclei, adiabatic, and nonadiabatic components

can hardly enable such an accuracy. For the four-body systems like deuterium molecule though, the nonrelativistic energy can also be calculated directly, that is without expansion in a mass parameter. Such calculations have been performed using nonadiabatic explicitly correlated Gaussian functions reaching the accuracy of $10^{-3} - 10^{-5}$ cm^{-1} [2,3]. On this poster, we present results of an approach employing nonadiabatic James-Coolidge basis functions. This method enables the accuracy of $10^{-7} - 10^{-8}$ cm^{-1} to be obtained for the nonrelativistic dissociation energy of an energy level and, in contrast to the aforementioned calculations, is not limited to the rotationless states. The new nonrelativistic results, augmented by relativistic and QED corrections, enable the accuracy which surpasses the best spectroscopic data [4-7].

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Session 1: Precision spectroscopy of atoms and ions / 25

Spectroscopy of HD+ and the Rydberg constant

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We consider recent experiments in the spectroscopy of the HD+ hydrogen molecular ion [1,2] as well as most recent achievements in theory. We want to show how the Rydberg constant may be deduced from theory-experiment comparison with a relative uncertainty close to 15 ppt.

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Session 3: Exotic atoms / 15

The virtual-Delbruck-scattering potential for light muonic atoms

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Co-authors: Savely Karshenboim ; Valery Shelyuto [1]; Robert Szafron [2]; Vladimir Ivanov [3]

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Light-by-light contributions to the Lamb shift in light muonic atoms were some time ago considered in [1,2]. Those include the so called Wichmann-Kroll potential and the virtual Delbruck scattering in nonrelativistic approximation. The result for the latter was presented in term a few master integrals in momentum space with complicated spectral functions. Here we investigate the potential induced by virtual Delbruck scattering in coordinate space in static-muon approximation. We find asymptotics at low and large distances (comparing with the Compton wave length of electron) and give a simple Pade-appriximation for the related potential. The results have been recently published in [3].

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Session 11: Miscellaneous / 8

Paving the way for bound-state QED tests in singly ionized helium

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Paving the way for bound-state QED tests in singly ionized helium

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Abstract:
For several decades bound-state quantum electrodynamics has been tested successfully by laser spectroscopy experiments on hydrogen. These measurements nowadays reach a relative precision of down to 10^{-15}. At this level of precision the value of the proton radius, as well as difficult-to-evaluate higher-order 2-loop QED terms play an essential role and limit future improvements. About 10 years ago the CREMA collaboration has measured the proton radius in muonic hydrogen and shook the community with a result which is in strong disagreement with the current CODATA value. The CODATA value combines several measurements with electronic hydrogen. Many atomic physics research groups are currently working towards understanding this puzzle.

We are developing the next generation of bound-state QED tests based on high precision measurements in singly ionized helium. We aim to measure the 1S-2S transition frequency in the extreme ultra-violet of a single trapped He^+ ion to an accuracy of below 1\,kHz. Due to the twofold nuclear charge, this measurement is very sensitive to the above mentioned QED terms. In combination with nuclear charge radius experiments conducted in muonic helium ions our results will set a benchmark for future QED calculations or can be used as a crosscheck concerning the proton radius puzzle.

We will measure the 1S-2S transition using the Ramsey-Comb Spectroscopy (RCS) method. RCS uses two amplified and upconverted pulses from the pulse train of a frequency comb laser to perform a Ramsey-like excitation. In this talk I will give an overview of the experiment and present recent results from measurements on xenon where we use pulse pairs upconverted to 110\,nm by high-harmonic generation (HHG). With

these measurements we reach an accuracy of below 1\,MHz, which is unprecedented with a light source from HHG. The HHG will later be extended to the XUV range, in order to create light at a wavelength of 32\,nm for the measurement in He^{+}.

Poster session / 67

Generating Sub-Millidegree Thermal Stability over Large Volumes for Precision Experiments

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Session 11: Miscellaneous / 13

Testing Quantum Calculations with Measurements on Radioactive Molecular Hydrogen Isotopologues

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Molecular hydrogen, including its radioactive tritium-containing isotopologues, is a testing ground for quantum calculation in molecules. High precision coherent anti-Stokes Raman scattering (CARS) measurements were performed on the Q-branch fundamental vibrational splittings of heavier tritium-containing isotopologues, T_2 and DT with an uncertainty < 0.0004 cm^{-1}, a 250-fold improvement over previous work. These measurements are compared to first-principles calculations with improved treatment of nonrelativistic, relativistic and quantum electrodynamic energy contributions, with a total uncertainty of 0.00011 cm^{-1} for DT. The experimental results showed good agreement with the calculations, yielding an averaged difference < 0.0002 cm^{-1} that is below the combined uncertainty. High precision studies on these heavier species could help disentangling various mass-dependent terms in the calculations.

Session 10: Gravity, new measurements / 1

Determination of G with time-of-swing method by using high-Q silica fibers

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Session 10: Gravity, new measurements / 10

Rotating-torsion-balance test of the weak equivalence principle - CANCELLED

Author: Lin Zhu[1]

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Rotating-torsion-balance test of the weak equivalence principle

Lin Zhu,1, 2 Qi Liu,1, 2 Hui-Hui Zhao,2 Shan-Qing Yang,2, 1 Cheng-Gang Shao,2, 1 Liang-Cheng Tu,2, 1 and Jun Luo3, 2

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The equivalence principle (EP) is the foundation of a wide class of gravitational theories including Einstein's theory of general relativity. However, the EP is suggested to be violated in most attempts to connect general relativity with the standard model. Here we present a test of the equivalence principle for the left and right-handed quartz crystals using a rotating a torsion balance. The result shows that their gravitational acceleration difference towards Earth
Δaleft-right = [−1.7 ± 4.1(stat) ± 4.4(syst)] × 10−15 m ·s−2 (1-σ statistical uncertainty), correspondingly the Eötvös parameter η = (−1.2 ± 4.1) × 10 −13 .

Session 6: Magnetic moment, g factor / 56

Many-body study of g factor of boron-like argon

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Experiments on few-electron ions of heavy atoms are of great importance to test bound-state QED. In particular, the most accurate value of the electron mass (almost by two orders of magnitude more precise than the value from the independent measurements) has been obtained in the study of g factor of highly charged ion. An independent determination of the fine-structure constant α is expected from the g-factor measurements in few-electron ions. Combined experimental and theoretical studies of the g factor and hyperfine structure can be used to obtain the values of the nuclear magnetic moments. In the present work we consider boronlike argon $40Ar^{13+}$ ion. Experimental study of its g

factor at ground and first excited states are in preparation at the Max-Plank-Institut für Kernphysik. Previously three different theoretical values of g factor have been reported with difference in order of 10^{-4}, which is within the accuracy of experiment. So, independent calculation of boronlike argon g factor was necessary.
We performed g-factor calculation of $40Ar^{13+}$ within Dirac-Coulomb-Breit Hamiltonian. To consider electron correlation effects at high level of accuracy coupled cluster approach was applied with single and multiple reference determinants. All electronic excitations up to full CI approach were considered, and fast convergence was achieved. Dirac-Fock calculations were performed within Gaussian basis sets. Breit interaction matrix elements were calculated by using four-index transformation technique, to reduce formal complexity of algorithm. Result of the present work proves one of three mentioned g-factor values and thus can be considered as independent confirmation.
Electronic and QED calculations were supported by the President of Russian Federation Grant No. MK-2230.2018.2, by the foundation for the advancement of theoretical physics and mathematics "BASIS"grant according to the research project No. 18-1-3-55-1, by RFBR Grant No. 16-02-00334, and by SPbSU-DFG Grant No. 11.65.41.2017 / STO 346/5-1. Development of the code to compute Breit interaction integrals was supported by the Russian Science Foundation Grant No. 18-12-00227.

Session 11: Miscellaneous / 30

Quantum-quasiclassical model for resonant and cooling/heating processes in atom-ion traps (CANCELLED)

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In recent years, there has been a rapidly growing interest in ultracold hybrid atomic-ion systems. It is caused by new opportunities opening here for modeling various quantum system and processes with controllable properties. Particularly, in the paper of Melezhik and Negretti 1 the confinement-induced resonances (CIRs) in ultracold hybrid atom-ion systems were predicted. The prediction was done in the "static approximation"for the ion. This approximation was also used in recent paper [2] where CIRs in two-center problem were analyzed in pseudopotential approach. However, going beyond the "static approximation"is a hot problem due to principally unavoidable effect of the ion "micromotion"in the Paul trap [3].
To adequately describe the atom-ion dynamics in the hybrid atom-ion trap we have developed a quantum-quasiclassical approach. In this computational scheme, the time-dependent Schrödinger equation, describing collisional atom dynamics in a waveguide-like trap, is integrated simultaneously with the classical Hamilton equations for the ion motion in a linear Paul trap. At that, the three-dimensional Schrödinger equation is coupled with the six classical Hamilton equations during the confined atom-ion collision. The computations were performed for two kinds of the ion confining trap. First, we have considered the effective trap with the time independent frequencies. Afterward, we have evaluated the effect of the ion "micromotion"on the CIRs by including oscillating term in the Paul trap. It was shown that the confined motion (and "micromotion") of the ion does not destroy the CIR. The shift of the CIR position as a function of the mean transversal and longitudinal ion energy were calculated. We also suppose to discuss an extension of the developed approach for heading/cooling process in the confined atom-ion systems. It is important problem for planning controllable and precision experiments with such systems [3].

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Session 6: Magnetic moment, g factor / 52

Measurement of muon's g-2 and EDM

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Anomalous magnetic moment (g-2) and electric dipole moment (EDM) of muon are sensitive tools to study the existence of physics beyond the standard model of particle physics. The Fermilab g-2 experiment is currently running to measure g-2 of positive muon with the muon beam at the magic momentum 3.1GeV/c in a 14 m-diameter storage ring.
The J-PARC g-2/EDM experiment aims to measure g-2 and EDM with a novel technique utilizing a low-emittance
muon beam with momentum set at 0.3 GeV/c and a 66 cm-diameter compact muon storage ring without focusing electric field. Achievements, present status, and prospects of these experiments will be presented.

Session 10: Gravity, new measurements / 43

Newtonian Gravitation Constant: History of Measurement and New Results

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The Newtonian gravitational constant G is one of the fundamental constants of nature. Accurate knowledge of this constant is not only of considerable methodological interest, but is also important due to the key role which it plays in gravity, cosmology, geophysics. The first experiment to measure the gravitation constant with a relative uncertainty of 1% has been performed in 1798 by Henry Cavendish, outstanding English scientist. A significant contribution to the measurement of G was made by the outstanding Hungarian physicist Roland Eötvös. 100 years after Cavendish, in a series of the experiments, he increased the accuracy of the G value in five times. To date, more than 200 experiments of the G measurement have been performed, including the experiments of Moscow University and Huazhong University of Science and Technology, but an accuracy of G value increases very slowly, only about 10 times in a century. So large discrepancies between different experimental values of G seems to be explained by the presence of systematic errors in the results of different experiments. One of the ways to solve this problem is to measure G simultaneously using different methods and different experimental setups.

Two independent experiments for G measurement have been performed at Huazhong University of Science and Technology (China). Two values of the gravitational constant with relative uncertainties of 11.6×10-6 were obtained in these experiments. These two G values coincide with each other on the 3σ confidence. The obtained result allows to assume with a high probability that the measured G value is free from systematic errors. The results were published in Nature, 560 pp. 582-588 (2018).

Session 4: QED tests on atoms and molecules / 23

Testing fundamental interactions with the helium atom

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The fundamental interactions theories can be verified at the low energy scale
by comparison of accurate calculations of atomic transition frequencies with experimental values.
Helium atom has several, so called forbidden transitions, which can be accurately measured.
I will present results of very accurate calculations of these transitions with comparison
to the most recent measurements and demonstrate intriguing discrepancies
for all the transitions involving D-states. These discrepancies, most probably,
will require further experimental verifications.

Session 2: High energy physics: experiment / 70

New States in Charmonium and Bottomonium Families

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We present recent results on new quarkonium states in electron-positron and hadron colliders. We discuss the status of both exotic charmonium and bottomonium states. Our review covers new results from Belle, BaBar, BESIII and LHCb Collaborations and brief discussion of perspectives for future experiments Belle-II and Super-Tau-Charm factory in Novosibirsk.

Poster session / 74

Algorithm for calculating Bethe logarithm and adiabatic correction for atoms and two-centered molecules

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Bethe logarithm is a component of one of the leading quantum electrodynamic energy correction for atoms and molecules. This correction is of the order of α^3.

A method for calculating the Bethe logarithm is presented. It is an alternative to the method of Schwartz \cite{Schwartz} which has been used in most of the atomic and molecular calculations. The present method was introduced in the paper by M Stanke et al. \cite{Stanke}. It is based on spectral decomposition of the operator that appears in the Bethe correction. In the present work we implement the method in calculations of bound electronic states of multi-electron atoms and two-centered molecules. A similar method is also used to calculate the adiabatic correction. All calculations presented here are done using an approach based on the Born-Oppenheimer approximation. The wave functions are expanded using all-electron explicitly correlated Gaussian functions with shifted centers. The problem of selecting appropriate basis sets for the spectral decomposition of the Bethe-logarithm operator is discussed. Tests are performed to find the most effective approach.

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Session 2: High energy physics: experiment / 58

Precision tests of the SM at ATLAS and CMS

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Opening / 63

Opening on behalf of the Roland Eötvös Physical Society

Author: András Patkós[1]

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Session 6: Magnetic moment, g factor / 76

The muon g-2 and the MuonE project

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After reviewing the theoretical status and the sources of uncertainties of the muon anomalous magnetic moment, I will present the idea of the experiment proposal MUonE aimed at a new determination of the Hadronic Leading Order contribution to the muon g-2. In particular the theoretical challenges related to the proposal will be discussed.

Session 3: Exotic atoms / 35

FAMU: latest results in the measurement of the transfer rate from mu-p to higher-Z elements

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The main goal of the FAMU experiment is to measure for the first time the hyperfine
splitting of the muonic hydrogen ground state and, through this measurement, to determine the

proton Zemach radius. To achieve this result, it is necessary to characterize first the muon transfer mechanism from muonic hydrogen to higher-Z elements. This study has been carried on by the FAMU collaboration at the RIKEN-RAL muon facility in UK. In this work the most recent results on this topic are presented.

Session 3: Exotic atoms / 79

Muonic atoms and proton size

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Randolf Pohl (JGU Mainz) for the CREMA Collaboration and the Garching Hydrogen Project

Muonic hydrogen atoms have for a long time been recognized as the ideal tool to study nuclear properties such as charge radii, (magnetic) Zemach radii, or nuclear polarizabilities. Our laser spectroscopy measurements of the Lamb shift in light muonic atoms (H, D, He-3 and He-4) have yielded charge radii with tenfold improved precision. Intriguingly, the proton and deuteron charge radii display large discrepancies to the
previous world average from laser spectroscopy of regular H and D atoms, and from elastic electron scattering. This "proton radius puzzle"has sparked a series of new measurements in regular atoms, such as the 2S-4P transition of atomic hydrogen we have measured in Garching. More
measurements are underway.

On the muonic side, a measurement of the hyperfine splitting of the 1S ground state in muonic hydrogen (which is pursued by 3 collaborations world wide) will yield an order of magnitude improved value for the Zemach radius of the proton that encodes its magnetic properties.

In the future, laser spectroscopy of trapped atomic tritium could improve the triton charge radius by a factor of 300, providing the "missing link"between our precise measurements of H and D on the one hand, and He on the other. Laser spectroscopy oftrapped atomic tritium could improve the triton charge radius by a factor of 300, providing the "missing link"between our precise measurements of H and D on the one hand, and He on the other. Laser spectroscopy of muonic Li and Be ions could improve the corresponding charge radii by a factor of 10. These results would provide highly accurate charge radii required for QED tests in simple atoms, ions, and molecules, and enable new high-precision benchmarks for ab initio nuclear structure calculations.

Session 10: Gravity, new measurements / 57

Bohr-Weisskopf effect in the thallium atom

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One of the quantities measured with high precision in heavy atoms (and low-atomic molecules) is the hyperfine splitting constant. For the most accurate theoretical prediction of this splitting one has to take into account nuclear structure contributions. These are contributions from the distribution of the charge (Breit-Rosental effect) [1, 2] and magnetization (Bohr-Weisskopf effect) [3, 4] over the nucleus. We show that these effects can be taken into account using the Gaussian basis set for electronic structure calculations.

In addition, a study was made of the hyperfine magnetic anomaly –a special combination of hyperfine constants and g-factors of 2 different isotopes, sufficiently sensitive to differences in the distribution of magnetization. As is known, the ratio of anomalies for two different electronic states is stable with respect to the choice of the nuclear model and its parameters. This fact is employed to predict the magnetic moments of short-lived isotopes. The obtained values are in a good agreement with the previously obtained estimates.
Atomic calculations were performed with the support of the grant of the Russian Science Foundation (project 18-12-00227). The calculation of the matrix elements of the hyperfine structure was carried out with the support of the grant of the President MK-2230.2018.2

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Session 4: QED tests on atoms and molecules / **45**

Quantum Electrodynamics of the hydrogen molecule

Author: Mariusz Puchalski[1]

Co-authors: Pawel Czachorowski [2]; Jacek Komasa [1]; Krzysztof Pachucki [3]; Anna Spyszkiewicz [1]

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Theoretical studies of hydrogen molecule is the cornerstone of ultraprecise quantum chemistry. Due to its simplicity, the achieved precision is the highest among all molecules and still has a potential of significant enhancement. This high precision of theoretical predictions for hydrogen molecules allows to improved tests of quantum electrodynamics (QED), and opens perspectives for determination of fundamental physical constants from its spectra. We search for discrepancies between highly accurate spectroscopic measurements for the hydrogen molecules and theoretical predictions based on QED, in order to discover new effects or even new interactions. We will present the latest advances in calculation reaching the level of 1 MHz for the dissociation energy.

Poster session / **72**

Precision measurements of the (anti)proton mass and magnetic moment by the BASE collaboration

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The measurement of the masses and magnetic moments of the antiproton and the proton is a sensitive test of CPT invariance and the determination of fundamental constants. In our experiments we store and detect a single (anti)proton in cryogenic Penning traps with storage times longer than one year. We have performed the most precise comparison of the proton and antiproton charge-to-mass ratios with 11 significant digits in measurements of their cyclotron frequencies. The proton and antiproton magnetic moments (g-factors) are measured by detection of spinflip quantum jumps via the continuous Stern-Gerlach effect in a Penning trap observing tiny differences in the axial

frequency of the trapped particles. With our trap set-ups in Mainz and at CERN we determined the antiproton and proton g-factors with a fractional precision on the ppb-level and better.

Session 7: Fundamental constants, atomic properties / 73

Precision measurements of the (anti)proton mass and magnetic moment by the BASE collaboration

Author: Wolfgang Peter Quint[1]

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The measurement of the masses and magnetic moments of the antiproton and the proton is a sensitive test of CPT invariance and the determination of fundamental constants. In our experiments we store and detect a single (anti)proton in cryogenic Penning traps with storage times longer than one year. We have performed the most precise comparison of the proton and antiproton charge-to-mass ratios with 11 significant digits in measurements of their cyclotron frequencies. The proton and antiproton magnetic moments (g-factors) are measured by detection of spinflip quantum jumps via the continuous Stern-Gerlach effect in a Penning trap observing tiny differences in the axial frequency of the trapped particles. With our trap set-ups in Mainz and at CERN we determined the antiproton and proton g-factors with a fractional precision on the ppb-level and better.

Session 7: Fundamental constants, atomic properties / 32

High-Precision Measurement of the Deuteron's Atomic Mass

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The rest masses of many light nuclei, e.g. the proton, deuteron, triton and helion are of great importance for metrology as well as in testing our current understanding of physics. For example the mass difference of triton and helion is used in an essential consistency check for the determination of the electron
antineutrino rest mass in the KATRIN experiment 1,[2]. However, light ions are also especially challenging to measure because of sizable systematic frequency shifts originating in the relatively large ratio of kinetic energies compared to the low rest mass. Recently discussed discrepancies in light ion mass measurements, carried out at different mass spectrometers and sometimes termed "light ion mass puzzle"[3], give further motivation for independent measurements.
A new ion trap setup termed as LIONTRAP (Light ION TRAP), dedicated to high-precision mass measurements of light ions, has been constructed in an MPIK-GSI-University of Mainz collaboration.
We recently measured the proton's atomic mass by comparing the cyclotron frequencies of a single proton and a bare carbon nucleus [4], achieving a relative mass uncertainty of 3.2×10^{-11}, a factor of three more precise than the CODATA value [5], and revealing a 3σ deviation with respect to this value. This, however, is not enough to resolve the "light ion mass puzzle".
After a phase of upgrading the experiment we are currently measuring the deuteron's atomic mass in a similar manner compared to the proton mass campaign. The upgrades include a novel method of improving the magnetic field homogeneity as well as improved stability.
At this conference I want to discuss LIONTRAPs performance with the new upgrades. I will also

present the systematic error budget of the deuteron measurement campaign, which is well below 1×10^{-11} relative, as well as preliminary results of the measurement.

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Session 6: Magnetic moment, g factor / 41

A New Experiment for the Measurement of the g-factors of 3He2+ and 3He+

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We construct a new experiment aiming at the first direct high-precision measurement of the 3He2+ nuclear magnetic moment μHe with a relative precision of 10−9 or better as well as an improved value for the ground state hyperfine splitting of 3 He+ with a relative precision of 10−10 [1,2]. The direct measurement of μHe will complement hyper-polarized 3He as an independent magnetometer, which exhibits smaller systematic corrections concerning sample shape, impurities and environmental dependencies compared to water NMR probes. In our experiment we will apply methods similar to those used in proton and antiproton magnetic moment measurements [3,4].

Those techniques rely on the challenging detection of single spin flips. However, the spin-flip detection fidelity is limited by the ions'energy and if applied to μHe the methods would lead to an insufficient detection fidelity. Thus, we rely on sympathetic laser-cooling to deterministically decrease the ions'energy and a novel Penning trap design optimized for nuclear spin-flip detection.

The status of the experiment will be presented.

1 Mooser et al., J. Phys.: Conf. Ser. 1138, 012004 (2018)
[2] Schneider et al., Annalen der Physik 531, 1800485 (2019)
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Session 11: Miscellaneous / 19

QED with heavy ions: on the way from strong to supercritical fields

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The current status of tests of quantum electrodynamics with heavy ions is reviewed. The theoretical predictions for the Lamb shift and the hyperfine splitting in heavy ions are compared with available experimental data. Recent achievements and future prospects in studies of the g factor with highly charged ions are also reported. These studies can provide precise determination of fundamental constants and tests of QED within and beyond the Furry picture at strong-coupling regime. Recent theoretical results on the pair-creation probabilities in low-energy heavy-ion collisions are presented. Special attention is paid to tests of QED in supercritical regime. It is known that in slow collisions of two bare nuclei with the total charge larger than the critical value, Z_c >173, the initially neutral vacuum can spontaneously decay into the charged vacuum and two positrons. Detection of the spontaneous emission of positrons would be the direct evidence of this fundamental phenomenon. It is shown that the vacuum decay can be observed via impact-sensitive measurements of pair-production probabilities 1.

1 I. A. Maltsev, V. M. Shabaev, R. V. Popov et al., arXiv:1903.08546.

Session 3: Exotic atoms / 78

Present status of muonium hyperfine splitting in J-PARC

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Muonium is the bound state of a positive muon and an electron. Muonium Spectroscopy Experiment Using Microwave (MuSEUM) is a new precise measurement of muonium hyperfine structure (MuHFS) at Japan Proton Accelerator Research Complex (J-PARC).
There are two major motivations for this new measurement.
1. Test of the bound-state Quantum Electrodynamics (QED). Muonium is a purely leptonic system and the theoretical calculation of its hyperfine structure is more precise than that of hydrogen. By comparing the experimental result and the theoretical calculation, one can test the bound-state QED precisely.
2. Contribution to the search for BSM physics via muon g-2. Muon anomalous magnetic moment, aˆV, is known for the 3 sigma tension between the experimental value at BNL and the theoretical value from the standard model. Two new experimental projects to measure muon g-2 more precisely (100 ppb) are ongoing at J-PARC and Fermilab using a muon storage ring. To extract a, these storage ring experiments
need an input parameter, which can be precisely determined by the MUHFS spectroscopy. MuSEUM determines the parameter with a precision of 10 ppb, a factor of twelve improvement from the precursor experiment at Los Alamos Meson Physics Facility (LAMPF), without assuming the bound state QED is correct. The lack of the statistics was the most dominant source of the uncertainty in the precursor experiments at LAMPF. New intense pulsed muon beam at J-PARC has opened the opportunity to improve the experimental result. A new muon beam line at J-PARC, HLine, with ten times more muon intensity is under construction and will be ready for use in a few years. In future, more intense pulsed muon beam source can accelerate the improvement of the precision. In this presentation, we report the recent results of the measurement at very weak field and the study of the systematic uncertainty. We also mention the future prospect, including preparation for high field measurement.

Poster session / 18

Two-loop self-energy corrections to the g-factor of bound electrons

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The g-factor of bound electrons can be measured and calculated with high accuracy. Comparisons between the theoretical and experimental values of the g-factor allow precision tests of QED in the presence of strong electric background fields and the determination of fundamental constants.

We present the status of our ongoing calculations of the two-loop self-energy correction to the g-factor of the bound electron in hydrogenlike ions. This correction currently gives rise to the largest uncertainty of theoretical g-factor predictions. The interaction with the nuclear potential is taken into account non-perturbatively in our calculations, in order to achieve a high accuracy for the bound electron in heavy ions. We have obtained full results for the loop-after-loop diagrams, and partial results for the nested and overlapping loop diagrams. In the latter case, we treat the Coulomb interaction in intermediate states to zero and first order 1.

Our results will be highly relevant for planned g-factor measurements with high-Z ions in the near future as well as for an independent determination of the fine-structure constant from the bound-electron g-factor.

1 B. Sikora, V. A. Yerokhin, N. S. Oreshkina et al., arXiv:1804.05733v1 [physics.atom-ph] (2018).

Session 7: Fundamental constants, atomic properties / 53

High-precision calculations of hydrogen molecule

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Highly accurate excited state energies in H2 provide a reliable method for determination of its ionization energy. We present H2SOLV - our numerical package capable of high-precision calculations of Σ and Π bound states of H2. Based on efficient method for calculations of two-center two-electron integrals with wavefunction represented as a linear combination of explicitly correlated exponential (Ko{\l}os-Wolniewicz) functions, it allows for multithreaded, large-scale computations limited only by the computer resources available and can produce highly accurate results.

We present results of exemplary application of our computational method for obtaining accurate Born-Oppenheimer energies, as well as dynamic polarizability calculations for different hydrogen isotopologues and to variational calculations of splitting energy between the lowest states of H2 for studies of long-range asymptotics of exchange energy.

Session 2: High energy physics: experiment / 59

Precision measurements in Higgs sector at ATLAS and CMS

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Session 4: QED tests on atoms and molecules / 31

Testing QED with precision spectroscopy of the helium atom

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Precision spectroscopy in few-body atomic systems, like hydrogen and helium, enables the testing of the quantum electrodynamics(QED) theory and determination of the fundamental physical constants, such as the Rydberg constant, the proton charge radius, and the fine-structure constant.We perform an laser spectroscopy measurement of the 2^3S-2^3P transition of ^4He in an atomic beam.The new centroid frequency of the 2^3S-2^3P may lead to a determination of the nuclear charge radius of He(r_{He}) with a relative accuracy of 10^{-3},once the theoretical calculations for mα^7 corrections have been accomplished. This will enable a comparison of the r_{He} values obtained from electronic and from muonic helium in the future.

In order to further improve the accuracy of the measurement of the 2^3S-2^3P transition, for both ^4He and ^3He, to the level of sub-kilohertz. We have recently improved the set up. By optimise the vacuum structure, we have effectively increased the beam intensity of the meta-stable helium atom by a factor of 10. By adding the zeeman slower system, the longitudinal velocity of the helium atom is actively reduced to about 100m/s, and the influence of the first-order Doppler effect is further reduced. In addition, we recently present an experimental and theoretical study of the light-force shift in the measurements of the 2^3S-2^3P transition frequency. The systematic shift in the extrapolated result at the zero-field limit was analyzed. As a consequence of this effect, a correction of +0.50(80)kHz was added to our previous result on the 2^3S-2^3P transition frequency. Methods to suppress the light-force shift were also discussed, which will be applied in our new setup to improve the accuracy of the atomic helium spectroscopy. A more accurate determination of the 2^3S-2^3P transition frequency of ^4He and ^3He may help to resolve the present disagreements in the ^4He and ^3He nuclear charge radius difference.

Opening / 64

Roland Eötvös: Commemorative Year

Author: László Szarka[1]

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Poster session / 38

Measurement system of the new Eötvös experiment

Authors: György Szondy[1]; Gyula Tóth[None]; Lajos Völgyesi[None]; Gergely Barnaföldi[None]; Edit Fenyvesi[None]; Péter Harangozó[None]; Bálint Kiss[None]; László Somlai[None]; Péter Ván[None]

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In 2017 a small group of researchers from Wigner Research Centre for Physics of the Hungarian Academy of Sciences, Department of Geodesy and Surveying of Budapest University of Technology and Economics (BME), Society for the Unity of Science and Technology (SUST), involving the Department of Control Engineering and Information Technology of BME and other organizations, departments and experts decided to repeat the famous Eötvös-Pekár-Fekete (EPF) experiment with the original method of Eötvös, but using up-to-date instrumentation and data acquisitions techniques. The task to automate and enhance a measurement with an almost 90 years old, original Eötvös-Pekar torsion balance is really challenging. It includes not only the automatic change of orientation of the balance and automatically evaluating the human-readable scale to be able to execute long, automatic measurement programs, but precise manufacturing and measuring impactors of different materials, as well as several other measurements of the environment, like temperature, local and environment seismic noise, gravity gradient, and tilt changes due to tidal forces and rainfall, etc. All these information is to be collected, processed, correlated and evaluated in a common IT solution. Our poster outlines the task and the challenges.

Session 5: Beyond the Standard Model / 4

Superweak force

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We summarize the current status of particle physics, collecting the established deviations from the standard model of particle interactions both at the energy and the intensity frontier as well as in cosmology. We propose a specific U(1) extension of the standard model of particle interactions and discuss the possible consequences of the model concerning the observed deviations. We present ways to constrain the parameter space of the model partially.

Session 7: Fundamental constants, atomic properties / 3

Precise determinations of the strong coupling in lepton collisions

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We discuss the status of determinations of the strong coupling with special attention to using event shape observables based on data collected at the Large Electron Positron collider and theoretical predictions at highest accuracy available at present. We argue that such extractions can be competitive with lattice determinations if the observables are selected carefully such that both higher order perturbative as well as non-perturbative contributions are suppressed. We give a list of such observables and study one particular class–the soft groomed event shapes–in detail. We present predictions for the soft drop thrust and study the scale dependence as a function of the grooming parameters.

Session 8: The gravity experiment of Roland Eötvös / 51

Remeasurement of the Eötvös experiment - status and first results

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Co-authors: B. Kiss ; Cs. Égető ; E. Fenyvesi ; G. Péter ; Gergely Barnafoldi [2]; Gy. Gróf ; Gy. Szondy ; L. Deák ; L. Somlai ; P. Harangozó ; P. Lévai ; P. Völgyesi ; Péter Ván

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Roland (Loránd) Eötvös and his colleagues Dezső Pekár and Jenő Fekete made measurements (the EPF measurement) between 1906 and 1908 for validating the equivalence of gravitational and inertial mass. Ephraim Fischbach and his
colleagues reanalyzed the results of the EPF measurement in 1986 and discovered a correlation between the small violations and some atomic parameter. Experimental reproduction of this correlation was unsuccessful, but there is still no valid explanation of these differences in the EPF
results. Our analysis of the EPF experiment pointed to a possible bias that justifies repeating the tests under better conditions and using modern new technology. Another good reason for repeating the EPF measurements is that 2019 –as the 100th anniversary of Eötvös'death –is referred to as "Eötvös year". After two years of preparation, in May 2019 tests have been started in a controlled and undisturbed environment of the Jánossy Underground Laboratory at KFKI, 30 meters below ground level. We give a brief overview
of the gravity field bias, and report on the challenges, current status and first results of the new experiments.

Session 11: Miscellaneous / 11

Proton CT - a novel imaging tool in hadron therapy

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Cancer can be treated by radiation therapy, which means that the tumor is destroyed by irradiating it with photons or hadrons (protons or heavier nuclei). In hadron therapy, the organs surrounding the tumor receive a smaller dose than if the treatment is done by photons; however, to plan such a treatment the energy loss of hadrons in the surrounding tissue has to be known precisely. Usually this is calculated from images made with photons via CT measurements. Using photons for the calculations results in large uncertainties in the energy loss of hadrons, which restrains us from using such a treatment in the vicinity of critical organs. CT measurements done using protons would allow us to largely reduce these uncertainties, therefore reducing the unnecessary radiation dose received by the patient and making hadron treatment available for more types of cancer. I will

show the developments in Bergen of such a proton CT based on the ALPIDE sensor, which was originally developed for the Inner Tracking System of the ALICE detector.

Session 5: Beyond the Standard Model / 47

Isotope shift and atomic parity violation in the search for new physics

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Isotope-shift-related phenomena are an important way of probing nuclear physics models and they can assist the search for new physics. It has been recently suggested to use measurements of King plot nonlinearity in a search for hypothetical new light bosons, namely for long-range force carriers with couplings not proportional to the electric charge 1. However, one can find nonlinear corrections to the King plot appearing already in the standard model framework. We investigate contributions to the nonlinearity arising from relativistic effects in the isotope field shift, the nuclear polarizability, and many-body effects. Our predictions place theoretical sensitivity limits on the search for new interaction [2].

Another way of precisely testing the standard model are parity-nonconserving (PNC) effects in low-energy atomic experiments. These effects are notably sensitive to hypothetical extra Z'bosons and dark photons [3]. We estimate the relative contribution of nuclear structure effects and new physics couplings to the PNC spin-independent effects in atomic systems [4]. We present general expressions to assess the sensitivity of isotopic ratios to neutron skins and to couplings beyond standard model at tree level. The evaluation of related parameters is carried out for atoms of current experimental interest.

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Poster session / 49

Prospects of precision measurements with thorium ions trapped inside Coulomb crystals of $^{40}Ca^{+}$

Authors: Anna Viatkina[1]; Karin Groot-Berning[1]; Felix Stopp[1]; Georg Jacob[1]; Dmitry Budker[2]; Raphael Haas[3]; Dennis Renisch[3]; Jörg Runke[4]; Petra Thörle-Pospiech[3]; Wenbing Li[5]; Tom Kieck[3]; Christoph Düllmann[6]; Ferdinand Schmidt-Kaler[7]; Victor Flambaum[8]; Mikhail Kozlov[9]

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Nuclear properties of thorium offer an opportunity for a number of novel applications, such as direct laser excitation of the nucleus in the case of ^{229}Th, which may serve for the construction of a nuclear clock, and also for testing fundamental symmetries [1-4]. In the framework of the Trapping And Cooling of Thorium Ions with Calcium (TACTICa) collaboration, we present loading and trapping single $^{232}Th^{+}$ ions into a linear Paul trap, with thorium ions being inserted into small crystals of trapped $^{40}Ca^{+}$ ions, which provide sympathetic cooling [5]. Trapped $^{232}Th^{+}$ ions are identified in two ways: non-destructively, from the gaps in the laser-induced calcium fluorescence pattern of the crystal, and from a time-of-flight signal after their extraction from the Paul trap [6]. We further discuss the possibilities for future studies of ^{229m}Th ions and thorium-containing molecules.

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Session 5: Beyond the Standard Model / 60

Highlights of searches for new physics at ATLAS and CMS

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Session 9: Gravitational waves / 62

Gravitational waves and the Einstein Telescope

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Einstein Telescope is the European proposal of a new gravitational wave observatory 1. The planned sensitivity is over an order of magnitude above the sensitivity of LIGO and Virgo detectors, due to several improvements in the technology, like the larger arms and masses, the cryogenic operation

and the underground site. In the presentation I discuss the discovery potential of the instrument and survey the gravitational wave detection technology. The recent status of the planned various gravitational wave detectors is reviewed, too. Then the presentation focuses to the various aspects of site selection process, the challenges of the underground operation and the related Hungarian activity in the Mátra Gravitational and Geophysical Laboratory [2].

1 http://www.et-gw.eu
[2] P. Ván et al., Long term measurements from the Mátra Gravitational and Geophysical Laboratory, https://arxiv.org/abs/1811.05198

Poster session / 75

Eötvös balance operation presentation

Author: Lajos Völgyesi et al.[1]

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An original AutERBal type Eötvös balance is presented. The balance is operational, has Eötvös sensitivity 1 and was originally designed as a portable device for geophysical measurements.

Session 8: The gravity experiment of Roland Eötvös / 54

Torsion Balance and Remeasurement of the Eötvös Experiment

Author: L. Völgyesi[1]

Co-authors: Cs. Égető ; E. Fenyvesi ; G. Barnaföldi ; G. Péter ; Gy. Gróf ; Gy. Szondy ; Gy. Tóth ; L. Deák ; L. Somlai ; P. Harangozó ; P. Lévai ; P. Ván

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Loránd Eötvös began his first gravity experiments using the Coulomb/Cavendish balance. This balance can measure the degree of deviation of the equipotential surface from the spherical shape. Eötvös had the great idea to place one of the masses at the ends of the torsion beam to a lower level by hanging it from a wire and thus making the instrument sensitive to the horizontal gradient of the gravity too. First, a brief history and base principle of the torsion balance will be overviewed and then the principle of the Eötvös experiment concerning to equivalence of the inertial and the gravitational masses will be discussed. We decided on the occasion of the "Eötvös year"to repeat the equivalence measurement under better conditions and using modern new technology. We give a brief overview of the preparations of the experiments.

Session 8: The gravity experiment of Roland Eötvös / 37

GEE Lab's Equivalence Principle Experiment

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The GEE Lab at Washington University in St. Louis has been operating a prototype long-period torsion balance in a search for violations of Einstein's Equivalence Principle (EEP). We have continuously monitored the angular orientation of the torsion balance for over 115 days, resulting in a rich set of data. From this, we have extracted signals on the differential acceleration of two test bodies made of Al and Si02 in the Galactic gravitational field. The experience we have gained from this experiment suggest the need for improved thermal and magnetic shielding; it also gives us confidence that long-period torsion balances have the ability to significantly improve the bounds on violation of EEP. In this talk we will describe our instrument, analysis procedure, and how these experiences can be used to improve our next generation torsion balance.

Session 1: Precision spectroscopy of atoms and ions / 2

High precision non-relativistic calculations for the nP (5<=n<=10) states of lithium atom

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The non-relativistic energies of the low-lying states of lithium have been calculated to a relative accuracy of 10^{-15} [1, 2]. However, for higher-lying states, the accuracy in energy eigenvalues decreases significantly as the principal quantum number increases [3]. Drake has developed an effective method [4] to solve the Schrödinger equation of the Rydberg states of two-electron atomic systems, in which the "zeroth-order wave function"is included in the variational wave function. Following Drake, we extended his method to lithium and found that this "zeroth-order wave function" is essential in increasing the accuracy of the non-relativistic energies of the highly excited states of lithium. Taking the nP (5<=n<=10) states for example, the non-relativistic energies can be calculated to 13-14 converged digits; in comparison, we can hardly obtain 11 significant digits without using this "zeroth-order wave function". This method will supply us a feasible way to study the Rydberg states of three-electron atomic systems at a high precision level.

Session 3: Exotic atoms / 34

Precision measurements of antiproton and antihydrogen properties at CERN

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The CERN Antiproton Decelerator, the only source of low-energy cooled antiproton beams in the world, will be extended by the ELENA storage ring to provide even lower energy antiprotons, thus increasing the number of antiprotons trapped in charged-particle traps or low density gas. The

antiprotons are used for precision measurement or to form antihydrogen, the simplest anti-atom consisting of an antiproton and a positron, in order to perform tests of CPT symmetry or to directly measure the gravitational interaction between matter and antimatter for the first time. The talk will give an overview on the measurements of the antiproton magnetic moment and laser and microwave spectroscopy of antihydrogen, where first spectroscopy results have recently been obtained, and the garvity measurements under preparation.

Session 1: Precision spectroscopy of atoms and ions / 69

m(alpha)ˆ6 order spin-averaged effective Hamiltonian of hydrogen molecular ions

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Poster session / 71

Discussions at the posters

Session 4: QED tests on atoms and molecules / 80

Conference photo

Excursion to Tihany Abbey / 82

Sightseeing walk with tourguide

Excursion to Tihany Abbey / 83

Free time

Excursion to Tihany Abbey / 81

Travel up to Tihany abbey by sightseeing train