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Table of Contents

Monday 14th of May

Tuesday 15th of May

Wednesday 16th of May

Table of Contents

Thursday 17th of May

Friday 18th of May

Table of Contents

Poster Session, Monday 14th of May

Poster Session, Tuesday 15th of May

The CODATA 2017 Special Adjustment of the Fundamental Constants and the New SI

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Quantity	Value
h	$6.626\,070\,15 \times 10^{-34}$ J s
e	$1.602\,176\,634 \times 10^{-19}$ C
k	$1.380\,649 \times 10^{-23}$ J K^{-1}
N_A	$6.022\,140\,76 \times 10^{23}$ mol^{-1}

Table 1: The CODATA 2017 values of h, e, k, and N_A for the new SI

The international system of units (SI) has been slowly evolving from an artifact-based system to one based on values of fundamental constants and invariant properties of atoms. International consensus on the foundation of a new SI based on exactly defined values of the Planck constant h, elementary charge e, Boltzmann constant k, and Avogadro constant N_A was reached during the 24th meeting of the General Conference on Weights and Measures (CGPM). Progress in the accuracy and consistency of the research results has enabled the International Committee for Weights and Measures (CIPM) at its 106th meeting to recommend to the CGPM to proceed with the adoption of the new SI. This presentation summarizes the 2017 special least-squares adjustment performed by the Committee on Data for Science and Technology (CODATA) that determined the exact values of h, e, k, and N_A given in Table 1 based on relevant data that was available by 1 July 2017. These values are recommended to the 26th GCPM to form the foundation of the new SI when it meets on 13 – 16 November 2018.

A fundamental constant as basis for the SI unit kilogram

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Only few weeks remaining, a 125 years old small cylinder of platinum-iridium, the International Prototype of the Kilogram, IPK, still defines the SI unit of mass. In November 2018 CGPM, the general conference on weights and measures, will meet to redefine four of the seven SI units on the base of fundamental constants. For the kilogram the Avogadro experiment provides a link of the kilogram to the atomic mass constant m_u by counting atoms in a given amount of mass – here a kilogram of a ^{28}Si single crystal. But how to "count" 10^{25} atoms as the age of the universe is only 10^{17} seconds? The solution is a crystal – a very good crystal of best purity, highest quality and perfection of crystalline order. With this it is possible to calculate the number of atoms if one only knows the distance of the atoms in the crystal and the macroscopic dimension of an artifact of this crystal. For the determination of Avogadro's constant, a sphere was chosen. Silicon crystals, which occur face-centered cubic, are available in high perfection by special institutes for crystal growth and the form of a sphere was selected as the obvious form of a cube failed because of the stability of its edges.

For the measurement of the Avogadro constant [1] four quantities are to be determined:

$$N_A = \frac{M_{Si} \cdot V_{sphere}}{n \cdot v_{uc} \cdot m_{sphere}}$$, with n = 8 the number of atoms per cubic unit cell

Herein the quotient of macroscopic volume V_{sphere} and the volume of the unit cell v_{uc} of silicon atoms gives the number of atoms of that sphere. Mass of the sphere m_{sphere} and molar mass M_{Si} considering the mass of the entity so that the number of atoms per mole is derived.

The measurements are divided into crystal measurements which determine parameters typical for the whole silicon crystal, here the molar mass and the volume of the unit cell, and the properties which are related to the artifact produced from the crystal, here mass and volume of a test sphere.

For the measurement of the molar mass a new technique, the isotope dilution mass spectrometry IDMS, demanded highly isotopically enriched material to allow relative uncertainties at the 10^{-9} level. 99.99% ^{28}Si material was received from Russian institutes, unfortunately for a price of about 1 Mio €/1kg-sphere. The lattice parameter is determined by COXI, combined optical and X-ray interferometry. Probes of the crystal are arranged in a Laue interferometer and the movement is measured with an optical interferometer [2].

From a Si crystal two spheres are produced. They are manufactured with outstanding perfection regarding roundness, roughness and subsurface damage of the crystal. The spheres must be measured for mass and volume. For the mass the sphere is compared to the national prototype of kilogram, a Pt-Ir cylinder, considering different volume, surface and material. For the volume of the sphere an optical interferometer is used. It consists of two high performance objectives with spherical reference faces which spacing is determined. With the sphere inserted the resulting gaps between sphere and the respective objective are measured. This interferometer resolves deviations from roundness in the sub-nm range and yields full topographies of the silicon spheres. A relative volume uncertainty of $7 \cdot 10^{-9}$ could be achieved.

[1] G Bartl *et al*., Metrologia **54** (2017) 693–715
[2] E Massa *et al*., Metrologia **48** (2011) S37-S43

The best determination of the Boltzmann constant k by acoustic thermometry of helium-4 gas

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The SI unit of temperature will soon be redefined in terms of a fixed value of the Boltzmann constant k derived from an ensemble of measurements worldwide. We report on the best-ever and definitive determination of k using acoustic thermometry of helium-4 gas in a 3-litre volume quasi-spherical resonator at LNE-Cnam. The method is based on the accurate determination of acoustic and microwave resonances to measure the speed of sound at different pressures.

The principle of the experiment is as follows. A gas-filled quasi-spherical resonator (QSR) is maintained in a thermostat at a known temperature, here the temperature of the triple point of water $T_{TPW} = 273.16$ K or within a few millikelvin of it (measurements are corrected for the small difference by a temperature ratio, other terms being sufficiently constant at the required level of accuracy). Acoustic resonance measurements are performed at different pressures of helium gas while the radii of the QSR are measured using microwave resonances. Great care is taken to avoid impurities in the test gas: a gas purifying system supplies a continuous flow of pure helium to the resonator to remove outgassing impurities. The amount of the only impurity that cannot be removed by purification, helium-3, is determined by mass spectrometry of samples from the same bottle as that used for the experiment. Correction terms on acoustic and microwave measurements have been computed using carefully validated theoretical models, and applied to the acoustic and microwave signals.

From data and traceable thermometry we deduce the value of universal gas constant $R = 8.3144614(50)$ J·mol^{-1}·K^{-1}. Using the current best available value of the Avogadro constant [1], we obtain $k = 1.38064878(83) \times 10^{23}$ J·K^{-1} with $u(k)/k = 0.60 \times 10^{-6}$, where the uncertainty u is one standard uncertainty corresponding to a 68 % confidence level. This value is consistent with our previous determinations [2, 3, 4] and with that of the 2017 CODATA adjustment of the fundamental constants [5] within the standard uncertainties.

[1] D B Newell *et al.*, 2018 Metrologia **55** L13
[2] L Pitre *et al.*, 2017 Metrologia **54** 856
[3] L Pitre *et al.*, 2015 Metrologia **52** S263
[4] L Pitre *et al.*, 2011 Int J Thermophys **32** 1825
[5] Peter J Mohr *et al.*, 2018 Metrologia **55** 125

Precision Spectroscopic applications of cold molecular ions

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Cold molecular ions prepared by sympathetic cooling with laser-cooled atomic ions in an ion trap represent attractive systems for new spectroscopic experiments. The long trapping times (up to hours) and state lifetimes (up to minutes) [1,2] in an almost perturbation-free environment enable the long interaction times required for the study of "forbidden" spectroscopic transitions which have not been accessible before in molecular ions.

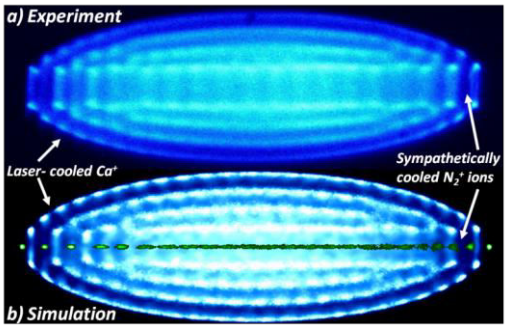

Figure 1: Bi-component Coulomb Crystal of Ca^+ and state-selected N_2^+ ions.

Here, we report the first direct observation of electric-dipole-forbidden, quadrupole- allowed infrared transitions in a molecular ion (N_2^+ in our case) [3], more than 60 years after such transitions have first been observed in a neutral molecule. The detection of these extremely weak transitions was enabled through a combination of the state-selective preparation of the molecular ions, their sympathetic cooling into the near-perturbation-free environment of a Coulomb crystal and the application of a highly sensitive charge-transfer detection scheme. The observed transitions in molecular ions can exhibit very small natural linewidths, rendering them ideal for spectroscopic precision experiments [4].

[1] X. Tong, A. Winney, and S. Willitsch, *Phys. Rev. Lett.* **105**, 143001 (2010).
[2] X. Tong, D. Wild, and S. Willitsch, *Phys. Rev. A* **83**, 023415 (2011).
[3] M. Germann, X. Tong, and S. Willitsch, *Nature Phys.* **10**, 820 (2014).
[4] Z.-X. Zhong, X. Tong, Z.-C. Yan, T.-Y. Shi, *Chin. Phys. B* **24**, 053102 (2015).

Interleaved Matter-wave Gyroscope with 2×10^{-10} rad.s^{-1} Stability

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Inertial sensors based on atom interferometry have the potential to address several applications ranging from navigation, tests of fundamental physics, gravitational wave astronomy, geoscience and metrology.

One important drawback of such sensors has been their reduced sampling rate, due to the cold-atom sample preparation, and to the long time of interrogation of the atoms in the interferometer which is required to achieve high inertial sensitivity. Here we report the interleaved operation of a cold-atom inertial sensor, where 3 atomic clouds are interrogated simultaneously in an atom interferometer featuring a 4 Hz sampling rate and a long interrogation time of 800 ms. Interleaving allows us to demonstrate a short term sensitivity of 30 nrad.s^{-1}.Hz$^{-1/2}$ in a matter-wave gyroscope of 11 cm^2 Sagnac area.

We also report a stability of 2×10^{-10} rad.s^{-1}, which competes, for the first time, with the best long-term stability level obtained with fiber-optics gyroscopes, and establishes cold-atom gyroscopes as a promising alternative to current technologies for inertial navigation.

Our experiment validates interleaving as a key concept in future atom-interferometry sensors aiming at probing time-varying signals, such as gravitational wave detectors, inertial measurement units, or gravity gradiometers.

Exploiting highly accurate frequency ratio measurements over coherent fiber links for exploring fundamental physics problems

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Frequency ratio measurements are key to improving the accuracy of optical frequency spectroscopy of nearly forbidden atomic transitions. These are transitions with sub-Hz linewidths ($Q \sim 10^{16}$) and the accuracy and uncertainty of these frequency measurements can be independently verified by comparison to each other. Frequency ratios can also be used to search for variations in fundamental constants, specifically the fine structure constant, α, and the proton/electron ratio [1]. Additionally, highly accurate frequency sources are beginning to be utilised in geodesy, where currently achievable spectroscopy of an atomic optical transition frequency down to a fractional uncertainty of 10^{-17} can be used to determine the height of the atomic frequency source above the geoid down to a resolution of 10 cm [2].

Atomic transitions are sensitive to environmental factors. Due to this sensitivity, it follows that utilising the least sensitive atomic species would be ideal. Hg was partially chosen as an atomic species for use in a clock at SYRTE due to its low sensitivity to blackbody radiation induced Stark shift and DC Stark shift. However, it is predicted that the role of non-linear lattice light shift is quite significant [3]. Strong control or good characterisation of external B- and E- fields are required to minimise the effects of Zeeman and Stark shifting when measuring a transition frequency. The SYRTE Hg clock is in a unique position of being able to access Sr clock frequency in-house, and Sr and Yb+ [5, 6] frequencies at PTB via utilising a phase compensated optical fiber network [5]. We will present improvements to the characterisation of systematic sources of inaccuracy and instability of the Hg optical lattice clock at SYRTE, including characterisation of lattice light shift by exploiting the Sr and Yb+ frequencies as accurate references. The Hg/Yb+ ratio is expected to be highly sensitive to variations in α, further incentivising the choice. Ultimately we reach a measurement of the ^{199}Hg $^1S_0 \rightarrow ^3P_0$ transition to a fractional uncertainty of the order of 10^{-17}. To support this, we will describe an improved uncertainty budget.

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[2] J. Grotti *et al.*, arXiv pre-print (2017) arXiv:1705.04089
[3] H. Katori *et al.*, Phys. Rev. A **91** (2015) 052506
[4] R. Tyumenev *et al.*, New J. of Phys. **18** (2016) 113002
[5] C. Lisdat *et al.*, Nature Communications **7** (2016) 12443
[6] N. Huntemann *et al.*, Phys. Rev. Lett. **116** (2016) 063001

Atomic photoexcitation by twisted light

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Photoexcitation with twisted light, *i.e.*, by a vortex light field that carries orbital angular momentum, excites atoms with quantum number transitions not possible with plane wave photons. Experiments have observed single trapped Calcium ions that serve as a localized and precisely positioned probe of the exciting field, and have observed the relative strengths of different transitions, depending on the ion's transverse position with respect to the center of the vortex light field [1, 2]. We calculate transition amplitudes initiated by a twisted light field using Bessel beam and other formalisms, and will show that the experimentally obtained transition amplitudes and the theoretical predictions agree at a level of better than 3% [2]. We will propose ideas to enhance the sensing accuracy of vortex modes in future experiments.

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[1] Christian T. Schmiegelow, Jonas Schulz, Henning Kaufmann, Thomas Ruster, Ulrich G. Poschinger, Ferdinand Schmidt-Kaler, Nature Communications **7** (2016) 12998.
[2] Andrei Afanasev, Carl E. Carlson, Christian T. Schmiegelow, Jonas Schulz, Ferdinand Schmidt-Kaler, and Maria Solyanik, New J. Phys. **20** (2018) 023032.

Antihydrogen 1S-2S laser spectroscopy

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I review the developments in the ALPHA collaboration leading to the first laser spectroscopy of an anti-atom [1] and resulting in the most precise measurement ever achieved on antimatter. The $1S_d$–$2S_d$ transition was excited via Doppler-free two photon absorption from a 243 nm laser coupled into a cryogenic optical enhancement cavity [2]. The sample consisted of magnetically trapped antihydrogen with an average kinetic energy around 300 mK. The obtained lineshape (see Fig. 1) allowed a frequency measurement with 12 significant figures, compatible with the hydrogen frequency projected and simulated at this environment and conditions. This is a direct test of the Charge-Parity-Time (CPT) symmetry to 2 parts in 10^{12}. As a comparison, in Fig. 2 we show the MIT spectrum on trapped hydrogen at 400 μK obtained in 1995 where a fractional resolution of 2 parts in 10^{12} was achieved [3]. It shows the prospects for improvement in these measurements with trapped species which could largely surpass [4] the present record accuracy of parts in 10^{15} using a 5.5 K beam of hydrogen [5]. We discuss the limitations in this initial measurement and ideas to proceed towards parts in 10^{15} by employing different techniques such as: (i) larger laser beam waist decreasing time-of-flight broadening and AC Stark shift with a lower intensity; (ii) larger samples or further cooling of the sample by Lyman–α [6], microwave [7], or other; and (iii) trapping hydrogen [8] in the same trap as antihydrogen allowing a direct comparison between the species in the same electromagnetic and gravitational environment.

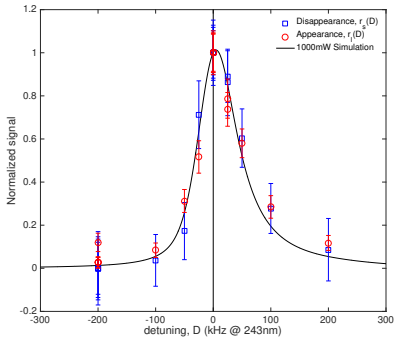

Figure 1: Lineshape obtained with trapped anti-hydrogen lineshape [1].

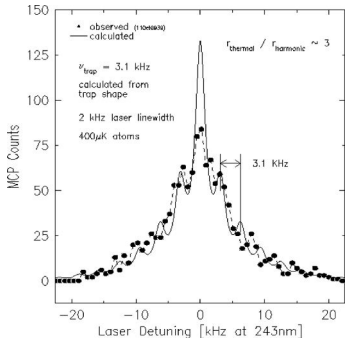

Figure 2: Lineshape from MIT's experiment [3] using trapped hydrogen at 400 μK

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[2] A. N. Oliveira *et al*., Rev. Sci. Instrum. **88**, 063104 (2017).
[3] C. L. Cesar *et al*., Phys. Rev. Lett. **77**, 255 (1996); and C. L. Cesar *et al*., Proceedings of the 5th Symposium on Frequency Standards and Metrology, J. Bergquist Ed., Cape Cod, Oct/1995, World Scientific (1995)
[4] C. L. Cesar, Phys. Rev. A **64**, 023418(2001)
[5] Parthey, C. G. *et al*., Phys. Rev. Lett. **107**, 203001 (2011).
[6] P. H. Donnan *et al*., J. Phys. B **46** (2013) 025302; I. D. Setija *et al*., Phys. Rev. Lett. **70**, 2257 (1993)
[7] C. L. Cesar *et al*., Phys. Rev. A 80, 041404(R) (2009)
[8] C.L. Cesar *et al*., J. Phys. B 49, 074001 (2016), doi:10.1088/0953-4075/49/7/074001

Measuring the Ground State Hyperfine Splitting of Antihydrogen

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CPT Invariance of the Standard Model dictates that the fundamental properties of particles and their anti-particles are equal. Antihydrogen is the simplest stable atom composed solely of antimatter and its corresponding matter partner hydrogen is one of the most precisely studied atomic systems. Consequently, a comparison of the spectra of hydrogen and antihydrogen issues one of the most stringent tests of CPT symmetry.

The ASACUSA (Atomic Spectroscopy And Collisions Using Slow Antiprotons) collaboration based at the Antiproton Decelerator at CERN aims to measure the ground state hyperfine splitting of antihydrogen in a Rabi-like experiment [1]. Antiprotons are accumulated in the MUSASHI trap [2] and then transported to the so-called double CUSP trap. In this mixing trap consisting of multi-ring electrodes and two pairs of anti Helmholtz coils, antihydrogen is produced by mixing antiprotons with positrons [3, 4]. The anti-atoms escape the trap as a polarised beam and enter the spectroscopy apparatus which comprises of a microwave cavity for inducing hyperfine transitions, a state-analysing sextupole magnet and an antihydrogen detector [5, 6] for monitoring the count rate of the arriving anti-atoms.

Spectroscopy and the goal to reach a relative precision at the ppm level is not yet feasible due to the low number of antihydrogen atoms produced in the ground state. Therefore, the present main focus lies on increasing the production rate and measuring properties of the anti-atoms created. In this talk the setup of the ASACUSA-CUSP experiment will be presented as well as its challenges and recent developments, including the first measurement of the quantum state distribution of antihydrogen atoms in a beam [7].

[1] E. Widmann *et al.*, Hyperfine Interactions **215** (2013) 18.
[2] N. Kuroda *et al.*, Phys. Rev. ST. Accel. Beams **15** (2012) 024702.
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[4] N. Kuroda *et al.*, Nature Communications **5** (2014) 3089.
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[6] C. Sauerzopf *et al.*, NIMA **A845** (2016) 579-582.
[7] C. Malbrunot *et al.*, RSA, DOI: 10.1098/rsta/376/2116 (2017).

[1] http://cern.ch/asacusa

Measurement of the hydrogen hyperfine splitting in a beam: results & prospects

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The goal of the ASACUSA CUSP collaboration at the Antiproton Decelerator of CERN is to measure the ground-state hyperfine splitting of antihydrogen down to relative precisions of $10^{-6} - 10^{-7}$ using an atomic spectroscopy beamline. A milestone was achieved in 2012 through the successful detection of 80 antihydrogen atoms 2.7 meters away from their production region. This was the first observation of "cold" antihydrogen in a magnetic field free region [1]. However the spectroscopy measurement is currently limited by the low flux of ground state antihydrogen atoms at the exit of the formation region [2].
In parallel to the work on the antihydrogen production, the spectroscopy beamline intended to be used for antihydrogen spectroscopy was tested with a source of hydrogen. This led to a measurement at a relative precision of 10^{-9} which constitutes the most precise measurement of the hydrogen hyperfine splitting in a beam [3]. This measurement also enabled to forecast the necessary conditions to achieve a measurement at the ppm level with antihydrogen.
The hyperfine splitting in hydrogen was determined using extrapolation of one of the ground state hyperfine transitions measured at different external magnetic fields. The apparatus has since been modified to allow simultaneous measurement of two transitions which in principle allows a determination of the zero-field hyperfine splitting will less atoms; something of great interest for the antihydrogen experiment.
I will review the experimental techniques used and the latest results obtained as well as the prospects for further measurements on hydrogen using the same apparatus for tests of Lorentz symmetry.

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[1] N. Kuroda *et al.*, Nature Communications **5**, 3089 (2014).
[2] C. Malbrunot *et al.*, Phil. Trans. R. Soc. A **376** 20170273; DOI: 10.1098/rsta.2017.0273 (2018)
[3] Diermaier *et al.*, Nature Communications **8**,15749 (2017)

Constraints for fundamental short-range forces from the neutron whispering gallery, and extention of this method to atoms and antiatoms

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Extra fundamental short-range interactions mediated by new bosons are predicted in many extentions of the Standard Model of particle physics. They are also predicted in theories with large extra spatial dimentions and theories involving the light dark matter hypothesis.

To search for such interactions at different charateristic distances, the experimentalists use many methods including measurements of gravitational interaction at short distances, the search for extra interactions on top of the van der Waals/Casimir-Polder interaction, the search for rare proceeses in neutrino detectors, precision measurements with atoms, molecules and neutrons. Comparison of the sensitivities of different experiments to extra short-range forces in the standard Yukawa parametrization is published, for example, in ref. [1].

A competitive method of searching at characteristic distances of about 10 nm is the precision measurement of the neutron whispering gallery [2]. This phenomenon is analogous to the well-known phenomenon of the whispering gallery of electromagnetic waves of a broad frequency range, as well as the sound wave. However, a material wave, for example a neutron wave, provides an additional possibility due to the existence of a nonzero neutron mass: for a neutron, the energy values of the whispering-gallery quantum states depend on the mass of the neutron and the interactions of this mass with the surface. Moreover, the neutron in such quantum states is localized at a distance from the surface of the order of tens of nanometers. Even a tiny extra force between the neutron and the surface at such distances would lead to a measurable shift in the energy of whispering-gallery quantum states.

We present the results of experiments performed with cold neutrons and estimate their sensitivity to extra short-range forces. We affirm that this method can also be extended to experiments with atoms and antiatoms [3]. The sensitivity of atomic experiments may be even higher than thus providing a similar, or even higher than the sensitivity of neutron experiments. More details could be found in [4].

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[1] I. Antoniadis *et al*., Compt. Rend. Phys. **12** (2011) 755.
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[3] A.Yu. Voronin *et al*., Phys. Rev. A **85** (2012) 014902.
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Tests of the theory of Quantum-Electrodynamics

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We describe recent developments in testing quantum-electrodynamics (QED), the theory of the interactions of matter with electro-magnetic fields and forces. The tests focus on consistency in the determination of parameters or constants within QED obtained via multiple independent means and, in particular, by comparisons of precision measurements with, equivalently accurate, theoretical calculations. The most-precise tests rely on a combination of the spectroscopy of atomic hydrogen, g-factor measurements of a free electron as well as that of an electron bound in a hydrogen-like ion, and finally the mass determination of the ions through atom recoil experiments and mass spectroscopy. These experiments determine the dimensionless finestructure constant and the mass of the electron to ten significant digits, orders of magnitude better than any other component of more unified models of nature. We also show that an international system of units (SI) based on fixed values of the Planck constant and the charge of the electron (in addition to the fixed value of the speed of light in vacuum) modifies the interpretation of some of these tests.

Nuclear recoil effect on the g factor of lithiumlike ions

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The nuclear recoil effect on the g factor of highly charged Li-like ions is studied [1, 2]. The fully relativistic quantum electrodynamics (QED) calculation of the one-electron recoil contribution to first order in the electron-to-nucleus mass ratio is performed. The two-electron part is evaluated within the lowest-order relativistic (Breit) approximation employing the novel four-component approach. The results for the two-electron recoil term are found to be in disagreement with the previous calculations based on the effective two-component Hamiltonian [3, 4, 5]. The obtained value for the nuclear recoil effect is used to calculate the isotope shift of the g factor of lithiumlike ${}^{A}\mathrm{Ca}^{17+}$ with $A = 40$ and $A = 48$ which has been recently measured [6]. As the result, the agreement between experiment and theory is significantly improved [1].

In addition, prospects for tests of the QED recoil effect on the g factor in experiments with heavy ions are studied [2]. It is found that, while the QED recoil effect on g-factor value is masked by the uncertainties of the nuclear size and nuclear polarization contributions, it can be probed on a few-percent level in the specific difference of the g factors of H- and Li-like heavy ions. This paves a way to test QED in a new region — strong-coupling regime beyond the Furry picture.

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Four loop QED contributions to the electron g-2

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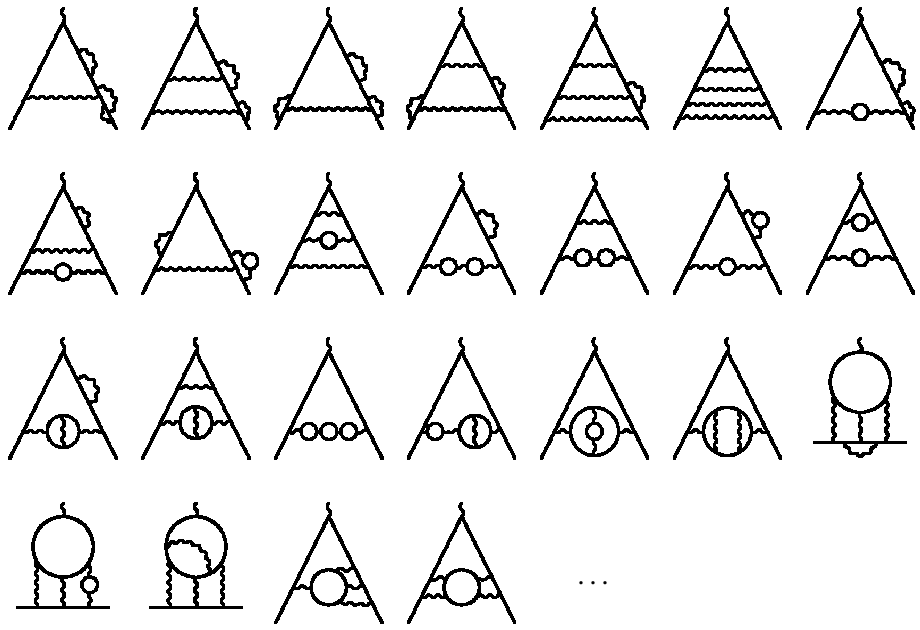
The anomalous magnetic moment of the electron is one of the physical quantities measured with the highest precision. Such high precision demands a similar precision in the theoretical evaluations in order to obtain stringent tests of QED. In this talk I will summarize the situation of the theoretical calculations of the contributions to the electron g-2; then, I will describe in detail the results of the twenty-year long project of the evaluation of all the 891 mass-independent four-loop QED Feynman diagrams contributing to the electron g-2 [1],



with the 1100-digits result

$$a_e^{QED}(\text{4-loop}) = -1.912245764926445574152647167439830054060873390658725345\ldots \left(\frac{\alpha}{\pi}\right)^4$$

and high-precision analytical fits. The consequences of this result on the QED tests and the determination of the fine structure constant will be also discussed.

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Precision Fundamental Physics with Trapped Antihydrogen

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Antihydrogen provides a unique tool for precision studies of fundamental physics. Or, so have we been promising for a long time. Finally, after many years of developments, we have reached the stage, in which precision measurements can actually be performed on antihydrogen. In this talk, I will give an overview of the ALPHA antihydrogen experiment, with some emphasis on hyperfine and Lyman-alpha spectroscopy, as well as our new initiative on gravity measurement. Our recent results on 1s-2s transition will be covered by Claudio Cesar in a separate talk.

Laser spectroscopy of cooled antiprotonic helium atoms

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The Atomic Spectroscopy and Collisions Using Slow Antiprotons (ASACUSA) collaboration at the Antiproton Decelerator facility of CERN is carrying out precise laser spectroscopy experiments on antiprotonic helium ($\overline{p}\mathrm{He}^+ \equiv \overline{p} + \mathrm{He}^{2+} + e^-$) atoms [1, 2, 3]. Employing buffer-gas cooling techniques in a cryogenic gas target, samples of atoms were cooled to temperature $T = 1.5$–1.7 K, thereby reducing the Doppler width in the single-photon resonance lines [3]. By comparing the results with three-body quantum electrodynamics calculations, the antiproton-to-electron mass ratio was determined as $M_{\overline{p}}/m_e = 1836.1526734(15)$. Besides providing a consistency test of CPT symmetry, the results have recently been used to set constraints on any exotic fifth force that may exist at the ~ 1 Å length scale [4, 5, 6, 7]. Further improvements in the experimental precision are currently being attempted.

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Constraints on exotic spin-dependent interactions between matter and antimatter from antiprotonic helium spectroscopy

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Spin-dependent interactions [1, 2] appear in theories including "new", i.e., so far undiscovered bosons. We have investigated the influence of these hypothetical potentials on the hyperfine structure in antiprotonic helium [3]. By comparing QED-based theoretical calculations [4] and precise spectroscopic measurements [5] we have found constraints on exotic spin- and velocity-dependent interactions between electrons and antiprotons. As a result, for the first time, semileptonic spin-dependent interactions between matter and antimatter have been constrained.

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High-precision comparisons of the fundamental properties of protons and antiprotons

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The Baryon Antibaryon Symmetry Experiment (BASE-CERN) at CERN's antiproton decelerator facility is aiming at high-precision comparisons of the fundamental properties of protons and antiprotons, such as charge-to-mass ratios, magnetic moments, and lifetimes. Our single-particle multi-Penning-trap experiments provide sensitive tests of the fundamental charge-parity-time invariance in the baryon sector.

Since our approval in 2013 we measured the antiproton-to-proton charge-to-mass ratio with a fractional precision of 69 p.p.t. [1], as well as the antiproton magnetic moment with fractional precisions of 0.8 p.p.m. [2] and 1.5 p.p.b. [3], respectively. At our matter companion experiment BASE-Mainz, we have performed proton magnetic moment measurements with fractional uncertainties of 3.3 p.p.b. [4] and 0.3 p.p.b. [5]. By combining the data of both experiments we provide a baryon-magnetic-moment based CPT test

$$\frac{g_{\bar{p}}/2}{g_p/2} = 1.000\,000\,000\,2\,(15),$$

which improves the uncertainty of previous experiments [6] by more than a factor of 3000. A unique antiproton reservoir trap used in BASE furthermore allows us to set constraints on directly measured antiproton lifetime [7]. Our current value $\tau_{\bar{p}} > 10.2\ a$ improves previous best limits by a factor of 30.

This talk I will summarize the recent achievements of BASE and give an outlook on future perspectives.

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A measurement of the proton mass by rotational spectroscopy of HD^+ molecular ions

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We have developed an approach that enables Doppler-free rotational spectroscopy of sympathetically cooled molecular ions in ion traps [1]. It makes use of the strong radial spatial confinement of molecular ions when trapped and crystallized in a linear quadrupole trap, providing the Lamb-Dicke regime for rotational transitions. We achieve a line width of 1×10^{-9}, an improvement by ≈ 50 times over previous highest resolution in rotational spectroscopy of ensembles of ions.

We have measured the absolute frequency of the fundamental rotational transition in HD^+, (v = 0, N = 0) → (v = 0, N = 1) (v, N are the vibrational and rotational quantum number, respectively) at 1.3 THz. We compare the value with the result of an *ab initio* calculation for this transition, which is proportional to the combination of fundamental constants $m_e/m_p+m_e/m_d$. Using CODATA2014 values for the deuteron mass and for the electron mass, we derive

$$m_p = 1.007\ 276\ 466\ 9(13)\ \text{u}\ .$$

The presentation will discuss the experimental technique, the result and the potential for further improvement.

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High-Precision Measurement of the Proton's Atomic Mass

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The electron, the proton and the neutron are the basic building blocks of the visible universe. The precise knowledge of their properties is of great interest for tests of fundamental physics and metrology.

To measure the proton's mass in atomic mass units, a new cryogenic fivefold Penning-trap setup was constructed, which is termed LIONTRAP (Light ION TRAP). It is the successor experiment of the former g-factor experiment for highly charged ions, which provided the most stringent tests of bound-state QED [1, 2, 3]. Moreover, it delivered the most precise value of the atomic mass of the electron [4].

The measurement principle is based on a phase-sensitive comparison of the proton's cyclotron frequency to that of a carbon nucleus ($^{12}C^{6+}$). To accomplish high precision a purpose-built doubly compensated Penning trap was set up, consisting of seven cylindrical electrodes. These electrodes serve to produce an extremely harmonic quadrupole trapping field by canceling out higher order electric field contributions using properly chosen voltages.

With a relative precision of 32 parts per trillion our result improves the current literature value by a factor of 3 and reveals a disagreement of about 3 standard deviations to it [5]. Additionally, the result affects the puzzle of light ion masses [6], but is not enough to explain the mass discrepancy of 4 standard deviations. At this conference, the new LIONTRAP setup as well as the latest results on the proton's atomic mass and the next major upgrades are presented.

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Hydrogen molecular ions and fundamental constants

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High-precision spectroscopy of hydrogen molecular ions has been proposed more than four decades ago as a way to determine the proton-to-electron mass ratio m_p/m_e [1]. This idea has not lost its relevance today [2], even considering the precision achieved in recent measurements of the electron and proton masses [3], but needs to be reanalyzed in the light of the current debate on the proton radius [4].

We have shown [5] that combined measurements in H_2^+ and HD^+ could be used to cross-check the proton/deuteron radii and Rydberg constant. To that end the theoretical accuracy should be improved to a few 10^{-12}; recent progress in the calculation of $m\alpha^8$-order QED corrections [6] has brought us closer to this goal. The most appropriate ro-vibrational transitions, experimental methods by which they can be measured, and experimental status will be discussed. Finally, the prospects of using hydrogen molecular ions as probes of a possible time variation of m_p/m_e will be reviewed [7].

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Precision spectroscopy of hydrogen molecular ions: present status of theory and perspectives.

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At present a theoretical prediction for the spin-averaged frequency of vibrational transitions in the hydrogen molecular ions (HMI) has reached a relative precision of $\sim 7.5 \times 10^{-12}$ [1]. On the other hand, recent experiment [2] on pure rotational transition in HD^+ has demonstrated the power of the Lamb-Dicke regime for precision spectroscopy of the HMI and potentiality in the nearest future to achieve a ppt level of spectroscopic accuracy. At the same time, it discloses new problems, which have to be solved in theory in order to comply with requirements of precision comparison with experiment. Namely, for pure rotational transitions it is essential to include into consideration the spin-dependent part of transition energy, which takes into account all corrections up to order $m\alpha^6$.

In our presentation we also discuss other problems, which are to be considered in order to improve theoretical predictions (by a factor of three at least). That will bring theoretical precision to the level better than the uncertainty in the Rydberg constant as determined by the CODATA14 adjustment of the fundamental constants [3].

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Quantum electrodynamic theory of the g factor of highly charged ions

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Quantum electrodynamic (QED) contributions to the electron g factor in strong binding fields have been tested recently to high precision in Penning trap measurements: an experiment with $^{28}Si^{13+}$ allowed to benchmark certain higher-order QED corrections for the first time [1], and constitutes one of the most stringent benchmarks of strong-field QED theory. Recently, the uncertainty of the electron mass has been largely decreased via measurements on the $^{12}C^{5+}$ ion, and by using the theoretical value of the g factor [2, 3]. In order to further reduce uncertainties in the theoretical description, we calculate further higher-order corrections, such as the higher-order remainder in $Z\alpha$ for the one-loop self-energy corrections [4], and parts of the two-loop Feynman diagrams [5, 6].

An independent and improved determination of the fine-structure constant α may also be possible in near future employing a weighted difference of the g factors of the H- and Li-like ions of the same element. This weighted difference in chosen to maximize the cancellation of detrimental nuclear effects between the two charge states. 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 [7]. We anticipate that the necessary theoretical accuracy can be reached by a combination of non-relativistic QED methods, and QED in the Furry picture ($1/Z$ expansion) [8].

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The ALPHATRAP g-Factor Experiment

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The ALPHATRAP experiment, located at the Max-Planck-Institute for Nuclear Physics in Heidelberg, Germany, aims to measure the g-factor of electrons in highly-charged ions with fractional uncertainties of 10^{-11} or below. This allows tests of bound-state quantum electrodynamics (BS-QED) in the extreme field region, for example by measuring the g-factor of the bound-electron of $^{208}Pb^{81+}$ in the 10^{16} V/cm field of the nucleus, and comparing it to theoretical predictions. It is a follow-up experiment to the Mainz electron g-factor experiment, which provided the most stringent of BS-QED [1] and the most accurate measurement of the electron mass [2].

The highly charged ions are bred in external electron-beam ion traps and transported through a room-temperature-to-4K beamline into a double-Penning-trap system. The trap system allows microwave and laser access for manipulating the motion and spin-state of trapped ions. An additional external ion source delivers $^{9}Be^{+}$ ions, which can be trapped simultaneously, laser-cooled with a 313 nm laser, and used for sympathetic cooling of the highly-charged ions. Trap characterization measurements using externally loaded ions demonstrated single-ion detection, sufficient stability of the trapping fields, and excellent vacuum conditions of better than 10^{-17} mbar. Further tests of laser- and microwave-manipulation of trapped ions are currently under way. An overview of the experiment will be given and progress towards a first measurement on the bound-electron g-factor of $^{40}Ar^{13+}$ will be discussed.

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A New Experiment for the Measurement of the *g*-Factors of $^3He^+$ and $^3He^{2+}$

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Recent dramatic advances in quantum-jump spectroscopy of single isolated nucleons in a Penning trap led to most precise measurements of the nuclear magnetic moments of the proton [1, 2] and its antimatter counterpart [3]. Based upon these successes a new experiment dedicated to the measurements of the electronic and nuclear magnetic moments of of $^3He^+$ and $^3He^{2+}$ is being set up at the Max-Planck-Institute für Kernphysik in Heidelberg (Germany). The project aims at the first direct measurement of the nuclear magnetic moment of $^3He^{2+}$ with a relative precision of 10^{-9} or better and an improvement of the ground-state hyperfine splitting in $^3He^+$ by a factor of 10 or better [4]. This will allow the establishment of hyper-polarized ^3He as an independent and accurate magnetometer, which up to now lacks a direct high-precision measurement of the nuclear magnetic moment. Furthermore a measurement of the ground-state hyperfine splitting in $^3He^+$ at a level of 10 ppt precision will complement the determination of nuclear structure effects in ^3He as persued in more sensitive but less precise experiments on muonic systems.
To date direct high-precision measurements of nuclear magnetic moments of single ions in a Penning trap have been demonstrated only for the proton and the antiproton. The employed methods rely on the detection of single spin flips whose detection fidelity is however limited by the radial mode energies of the single trapped particle. If applied to the magnetic moment of the three-times-heavier ^3He, the methods would hinge upon an insufficient detection fidelity. Thus, to meet the challenge of the high-fidelity spin-flip detection in this heavier system, the experiment aims to decrease the mode energy by more than two orders of magnitude compared to classical resistive cooling approaches. This will be achieved by applying sympathetic laser cooling, by coupling the single trapped ^3He ion to a reservoir of laser-cooled beryllium ions at their Doppler temperature. The scheme, which relies on a set of techniques proposed by Heinzen and Wineland [5], is based on the sympathetic coupling of the trapped ^3He ion to a cloud of $^9Be^+$ ions laser-cooled down to the Doppler limit. From this quasi-deterministic cooling scheme a considerable reduction in experimental cycle times and a high-fidelity spin state detection are expected.
In the contribution developments towards sympathetic laser cooling, including the demonstration of laser cooling of a cloud of $^9Be^+$ ions in a highly-advance five-Penning trap system, and the prospects towards the planned ^3He measurements will be presented.

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Towards high-precision spectroscopy of the 1S–2S transition in He^+

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The simplicity of hydrogen and hydrogen-like systems allows for extremely accurate predictions of their energy levels using bound-state quantum electrodynamics (QED). These theory values contain fundamental constants, most importantly the Rydberg constant and the nuclear size. By comparing theory and experiment, these constants can be determined and the validity of the theory itself can be tested.

The frequency of the extremely narrow 1S–2S two-photon transition was measured in atomic hydrogen with a relative uncertainty below 10^{-14} [1, 2]. This value can be combined with measurements of other transitions in order to extract values for the Rydberg constant and the proton size [3].

We are currently setting up an experiment to do spectroscopy of the 1S–2S transition in the simplest hydrogen-like ion, He^+. This could give new insights into a so-far unresolved discrepancy between different determinations of the proton charge radius which is known as the *proton radius puzzle* [4]. Furthermore, interesting higher-order QED corrections scale with large exponents of the nuclear charge which makes this measurement much more sensitive to these corrections compared to the hydrogen case [5]. Finally, He^+ ions are charged particles that can be trapped and cooled in an ion trap. This greatly reduces systematic effects due to particle motion that dominate the uncertainty in the hydrogen measurements.

However, driving this transition requires narrow-band radiation at 61 nm. This lies in the extreme ultraviolet (XUV) range where no refractive optics and no laser sources exist. We will therefore perform direct frequency comb spectroscopy by converting an infrared high power frequency comb to the XUV using high harmonic generation in a gas target. The He^+ ions will be trapped in a Paul trap and sympathetically cooled by co-trapped Be^+ ions.

This talk will give an overview of the planned experimental setup and report on its current status.

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Precision spectroscopy of the 2S-4P transition in atomic hydrogen

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Precision measurements of atomic hydrogen (H) have long been successfully used to extract fundamental constants and to test bound-state quantum electrodynamics. Both the Rydberg constant R_∞ and the proton root mean square charge radius r_p are determined to a large degree by H spectroscopy, requiring the measurement of at least two transition frequencies. With the very precisely measured 1S-2S transition frequency [1] serving as a corner stone, the current limitation of this extraction is the measurement precision of other H transition frequencies. Moreover, r_p extracted from the H spectroscopy world data disagrees by 4 standard deviations with the much more precise value extracted from spectroscopy of muonic hydrogen (μp) [2].

Using a cryogenic beam of H atoms optically excited to the initial 2S state, we measured the 2S-4P transition in H with a relative uncertainty of 4 parts in 10^{12} [3]. We motivate an asymmetric fit function, which eliminates line shifts from quantum interference of neighboring atomic resonances. Combining our result with the 1S-2S transition frequency yields the values of the Rydberg constant $R_\infty = 10973731.568076(96)\,\mathrm{m}^{-1}$ and $r_p = 0.8335(95)\,\mathrm{fm}$. Our r_p value is 3.3 combined standard deviations smaller than the previous H world data, but in good agreement with the μp value.

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Cw laser spectroscopy of the 1S-3S transition in hydrogen: new contribution to the proton radius puzzle

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High resolution spectroscopy of the hydrogen atom plays a key role in testing the theory of quantum electrodynamics, and in the determination of fundamental constants, such as the Rydberg constant or the proton charge radius. Since 2010, a disagreement has been found between the proton radius deduced from the spectroscopy of muonic hydrogen [1] and the CODATA-recommended value [2] relying on experiments conducted on electronic hydrogen (Fig. 1). To date still unsolved, this *proton radius puzzle* was even recently deepened by two new contradictory results in hydrogen spectroscopy: the 2S-4P transition frequency measured at MPQ [3], and the 1S-3S transition frequency measurement presented here.

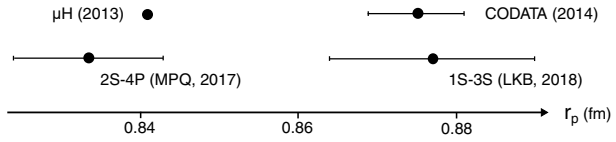

Figure 1: Proton charge radius values from hydrogen spectroscopy, with 1σ error bars.

In our experiment, the 1S-3S transition of atomic hydrogen is excited by two counter-propagating photons at 205 nm, in a Fabry-Perot cavity inside a vacuum chamber. An effusive beam of ground state hydrogen atoms at room temperature is directed colinearly with the axis of the cavity. We observe the 1S-3S resonance by detecting the Balmer α fluorescence at 656 nm. We use sum frequency generation in a BBO cristal to produce the cw laser source at 205 nm, by mixing a Ti:Sa laser at 894 nm and a frequency doubled Verdi laser at 532 nm. Their frequencies are measured using an optical frequency comb referenced to the LNE-SYRTE primary frequency standards thanks to a 3-km-long fiber link.

The main systematic effect to be considered is the second-order Doppler shift. It is corrected by fitting our experimental data with theoretical lineshapes taking into account the velocity distribution of the atoms in our effusive beam. This velocity distribution is determined by measuring the shift of the transition frequency when a transverse magnetic field is applied to the moving atoms, inducing a motional quadratic Stark effect [4]. Other systematic effects include a collisional shift, an AC Stark shift, and a recently evaluated quantum interference effect [5]. The overall uncertainty on the 1S-3S transition frequency is 2.6 kHz, that is a relative uncertainty of 9×10^{-13}. It yields a value of the proton radius that appears to support the CODATA-recommended value [6].

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Spectroscopy of hydrogen 1S-3S transition in cryogenic atomic beam

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Laser spectroscopy of atomic hydrogen is a source of valuable data for a least-square adjustment of fundamental constants and precise tests of QED. Further improvement of precision of those measurements is of key interests for a problem, known as a Proton Size Puzzle [1]. This work requires suppression of different systematic effects, including a Doppler shift. Cooling the atomic beams to cryogenic temperatures opens a possibility to decrease the velocities of atoms, reducing the uncertainty, caused by velocity distribution of the atoms.

We report about our experiment on two-photon spectroscopy of the transition 1s-3s in atomic hydrogen by frequency combs [2]. For the excitation of atomic transition we use a mode-locked Ti:Sa laser with two frequency doubling stages. The excitation takes place in a beam of atomic hydrogen expanding in a vacuum chamber. To reduce a first-order Doppler effect we use a technique of two-photon spectroscopy in counter-propagating laser beams [3]. Using a cryogenic nozzle, cooled down by liquid helium, helps us to decrease the velocity of atoms, improving systematic uncertainties in our experiment.

In the presentation we discuss main systematic effect which is presented in our experiment, namely the first-order Doppler shift caused by chirp of the laser pulses. We discuss modelling of this shift and model-independent approaches, allowing to eliminate this effect.

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Direct Frequency Comb Spectroscopy on Hydrogen and Associated Systematic Frequency Shifts

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High precision spectroscopy has been always the driving force for new fundamental theories in physics. The so called proton size problem is a so far unexplained disagreement of the value of the proton charge radius extracted from the muonic spectroscopy, hydrogen spectroscopy and elastic electron-proton scattering by more than 5 sigma [1]. Recently two new experiments intensified this puzzle [2], [3].

For the first time we present a high precision measurement in hydrogen on the 1s3s(F=1) performed with Direct Frequency Comb Spectroscopy (DFCS [4]), with an uncertainty sufficient to contribute to the Proton Size Puzzle. Systematic frequency shifts observed with DFCS differ significantly from previous measurements which utilize CW lasers and in particular from the previous 1s3s (F=1) measurement, allowing for the first time comparison of two different groups on the same transition for the proton size puzzle.

In our experiment we excite a cryogenic hydrogen atomic beam with a picosecond frequency comb. The UV frequency comb at 205nm is produced by quadrupling a TiSa comb at 820nm by two subsequent frequency doubling stages. While two-photon transitions are in principle Doppler free in first order, residual Doppler shift associated with chirped pulses is observed and constitutes our leading systematic. Other significant systematics are Second Order Doppler Effect, collisional shift and AC/DC Stark Effects. We present experimental determination of these systematics and comparison with the theory.

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Positronium precision spectroscopy: Measuring the 1s-2s and excited state hyperfine transitions

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Positronium is an excellent system to test bound state QED theory to very high precision, since it is almost exlusively governed by the electromagnetic force and does not exhibit the finite size effects which plague measurements of protonic atoms.

Numerous precise experiments have therefore been conducted in the past to measure the hyperfine splitting of Positronium. However, these experiments show almost 4σ disagreement with the most recent bound state QED calculations. PHySES' approach is to eliminate several possible sources of systematics present in earlier experiments by a novel experimental design to conclusively check this discrepancy.

Furthermore, measuring the 1s2s transition in Positronium would allow for a very stringent test of bound state QED in the ppb range. Current efforts to reach this sensitivity include upgrades to a pulsed positron beam and a novel time-of-flight detection scheme involving rydberg excitation of excited positronium.

Additionally, by comparing theory to experimental values gained by these experiments, one can test CPT and Lorentz violating effects and their corresponding coefficients in the Standard-Model extension (SME) complementary to those gathered by hydrogen spectroscopy.

This talk will report on the design, implementation, current status and future prospects of ongoing efforts at ETH Zurich to measure the 1s-2s and excited state hyperfine splitting in Positronium.

Higher Order Corrections to Positronium Energy Levels

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Positronium spectroscopy is of continuing interest as a high-precision test of our understanding of binding in QFT. Positronium represents the purest example of binding in QFT as the constituents are structureless and their interactions are dominated by QED with only negligible contributions from strong and weak effects. Positronium differs from other Coulombic bound systems such as hydrogen or muonium in having maximal recoil (the constituent mass ratio m/M is one) and being subject to real and virtual annihilation into photons. Spectroscopic studies of low-lying states ($n = 1$ hyperfine splitting, $n = 2$ fine structure, and the $2S - 1S$ interval) have reached a precision of order $1MHz$, and ongoing experimental efforts give the promise of improved results. Theoretical calculations of positronium energies at order $m\alpha^6 \sim 18.7MHz$ are complete, but only partial results are known at order $m\alpha^7 \sim 0.14MHz$. I will report on the status of the positronium energy calculations, give some details of the methods employed, and present the latest results for order $m\alpha^7$ contributions.

High precision measurement of muonium hyperfine structure

Toya Tanaka[a,b] on behalf of the MuSEUM collaboration

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Muonium is a hydrogen-like atom formed by a positive muon and an electron. Its 1S state hyperfine structure is evaluated with high precision both by theoretical calculations and experimental results. Therefore, muonium is suitable for a stringent test of the bound state QED of hydrogen-like atoms. MuSEUM (Muonium Spectroscopy Experiment Using Microwave) collaboration aims to measure the muonium hyperfine structure with high precision.

The Muonium hyperfine structure can be measured in two methods. One is to measure the spin transition frequency $\Delta\nu_{\mathrm{HFS}}$ in extremely low magnetic field (ZF). And the another way is to measure the spin transition frequencies $\Delta\nu_{12}$ and $\Delta\nu_{34}$ of the split states by the Zeeman effect in high magnetic field (HF). In the HF measurement, the muon-to-proton magnetic moment ratio (μ_μ/μ_{p}) and muon-to-electron mass ratio ($\mathrm{m}_\mu/\mathrm{m}_{\mathrm{e}}$) can be derived by $\Delta\nu_{12}$ and $\Delta\nu_{34}$. (Figure 1)

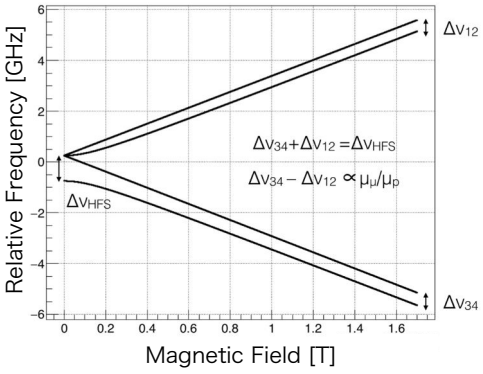

Figure 1: Breit Labi diagram of muonium

The previous research of MuHFS was performed at the former LAMPF (Los Alamos Meson Physics Facility) with 300 ppb in ZF [1] and 12ppb in HF [2]. Also μ_μ/μ_{p} and $\mathrm{m}_\mu/\mathrm{m}_{\mathrm{e}}$ are measured at HF MuHFS measurement with 120ppb [2]. Also μ_μ/μ_{p} is a important parameter to determine the precision of the muon anomalous magnetic moment (a_μ) measurement. a_μ is one of the physical properties which the experimental result differs from the theoretical calculation [3]. Therefore, MuHFS measurement is essential for the precision of a_μ. MuSEUM collaboration aims to measure both ZF and HF measurement and improve the precision by a factor of 10.

Previous measurements were constrained by statistical uncertainty. This problem is cleared by utilizing the intense pulsed muon beam at J-PARC MLF (Material and Life Science Experimental Facility) MUSE (Muon Science Establishment). MuSEUM collaboration is currently measuring MuHFS in ZF with our upgraded experimental system, and in parallel we are also developing the magnetic field mapping system for the future HF measurement. In this presentation I would like to introduce about the developments of the MuSEUM experiment and report the experimental status.

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Cold muonium atoms for future atomic physics and gravity experiments

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We are investigating methods to create a novel muonium (Mu) source, based on $\mu^+ \rightarrow \mathrm{Mu}$ conversion near to the surface of superfluid helium (SFHe). This source would have the potential of providing high brightness atomic beams for next generation Mu experiments, *e.g.* to increase precision of present Mu spectroscopy results [1, 2]. We are also investigating the feasibility of using such sources for measuring the gravitational interaction of Mu. The positive muon (μ^+) which is dominating the Mu mass is not only an elementary antiparticle, but a second-generation lepton too. This makes a gravity experiment highly motivated [3], and complementary to gravitational studies of antihydrogen [4, 5, 6] and positronium [7].

State-of-the-art Mu sources (like silica aerogel, mesoporous SiO_2) emit Mu atoms with a large (thermal) energy distribution, and wide ($\sim \cos\theta$) angular distribution. Cooling of these porous samples below 100 K results in rapidly declining numbers of vacuum-emitted muonium due to decreased mobility, and atoms sticking to the pore walls [8]. The advantage of using superfluid helium for Mu production at $T < 0.3$ K temperatures is the expected large chemical potential ($E/k_B \sim 270$ K) of the atom. This implies that in the vicinity of the surface, Mu would be ejected with relatively high (~ 6 mm/μs) velocities from the bulk to near-vacuum even at the lowest temperatures, while transverse momentum would remain low due to the cold media [9]. In this talk, methods and challenges to create such SFHe Mu sources, the present status, and the feasibility of an antimatter gravity experiment will be discussed.

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Accurate calculations with explicitly correlated functions for molecular hydrogen

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Theoretical studies of hydrogen molecule is the cornerstone of the molecular quantum mechanics. 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 H_2 leads to improved tests of quantum electrodynamics (QED) and improved bounds on hypothetical interactions [1]. Moreover, at the 10^{-7} cm^{-1} precision level the dissociation energy is sensitive to the proton charge radius, which may help to resolve the so called proton radius conundrum [2]. This requires high accuracy calculations of not only nonrelativistic energies, but also leading relativistic and QED, as well as the higher order QED corrections. In fact, the nonrelativistic energies can already be calculated with the precision of 10^{-7} cm^{-1}, as demonstrated in Ref. [3]. The the higher order QED contribution has very recently been calculated [4] using explicitly correlated Gaussian (ECG) functions with $1 + r_{12}/2$ prefactor (*rECG*) that makes the interelectronic cusp condition to be exactly satisfied. We provided improved results for the dissociation and the fundamental vibrational energies [5]. These results open the window for the high precision spectroscopy of H_2 and related accurate tests of fundamental interactions models. Recently, we also reported also highly accurate results for the leading relativistic correction using *rECG* functions [5] and conclude that the compilation of previous results in Ref. [6] has underestimated uncertainties. We will also present the latest advances in the calculation of nuclear mass relativistic corrections, which are currently the main limitation of theoretical predictions.

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Precision tests with molecular hydrogen and isotopes

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Molecular hydrogen has emerged as a benchmark quantum test system for fundamental physics, where current high-precision measurements challenge the most accurate theoretical calculations that include relativistic and quantum electrodynamics (QED) contributions. Investigations on isotopic molecular species containing deuterium and tritium provide opportunities to expand such fundamental tests, that will aid in unravelling important higher-order mass-dependent corrections as well as nuclear size contributions to the level energy structure. In the context of the long-standing Amsterdam program on precision measurements in molecular hydrogen, recent measurements on HD and T_2 will be presented. Extremely weak transitions in the $(v = 0 \rightarrow 2)$ overtone band of the HD molecule were measured with sub-Doppler resolutions to obtain transition frequencies with three orders of magnitude improvement in accuracy. In a second study, precision measurements on the fundamental $(v = 0 \rightarrow 1)$ vibrational splittings of the radioactive T_2 molecule were also performed yielding transition energies that are 250 times more accurate than previous studies. These benchmark values provide a test of QED theory in the hydrogen molecule, open up another avenue to pursue a solution to the proton radius puzzle, and point towards precision studies of nuclear structure. With further progress in the first principles calculations, future comparisons between experiment and theory will yield stronger constraints on new physics such as hypothetical fifth forces and extra dimensions.

Precision spectroscopy of HD at 1.4 μm

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The weak infrared spectrum of the heteronuclear diatomic molecule HD originates from the existence of a small electric dipole moment ($\sim 10^{-5}$ D), due to the inversion symmetry breaking in conjunction to the breakdown of the Born-Oppenheimer approximation. Since the HD has only two nuclei and two electrons, representing one of the simplest molecular systems existing in nature, it is possible to perform highly-accurate *ab-initio* quantum-mechanical calculations of its energy dipole transition levels and moments which take into account the violation of Born-Oppenheimer approximation by means of adiabatic and non-adiabatic corrections [1]. A quantum test system for fundamental physics can be obtained comparing HD precision measurements with advanced QED calculations which in turn puts constraints on a fifth force for a certain effective range [2].

In this work, a precision measurement of the HD electric-dipole first overtone band transition R(1) line-center frequency has been carried out implementing a new concept of frequency-stabilized cavity ring-down spectroscopy. It is based on the use of a pair of phase-locked extended-cavity diode lasers (ECDL) emitting in the wavelength range between 1.38 and 1.41 μm [3]. One of these acts as reference oscillator, being locked to a high-finesse cavity by means of the Pound-Drever-Hall (PHD) technique which in turn is locked to a self-referenced erbium-doped fiber-laser based Optical Frequency Comb Synthesizer (OFCS). The frequency of the probe laser is accurately scanned across the HD vibration-rotation transition, while an intrinsically stable high-finesse optical cavity tracks the laser frequency. Observing several repeated cavity ring-down events, absorption spectra have been recorded with high resolution, precision and fidelity. The cavity finesse determined under vacuum conditions is about 160000, which enables to get an optical path of 43.8 km. The measurements have been performed on a 97% ^{2}H-enriched hydrogen sample, at a pressure ranging between 1 e 15 Torr. As a result of a global fitting procedure of a manifold of spectra across the pressure range, the line center frequency has been determined to be 7241.849351(2) cm^{-1}, that is (217105181.75 $\pm$ 0.07) MHz. It agrees with the theoretical value 217105180 (2) MHz reported in [1].

Further measurements of the HD first overtone band absolute frequency lines will be attempted in the near future.

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Relativistic correlation and QED effects on the radiative decay of 1*s*2s3*s* configuration in Li-like ions

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Fully relativistic configuration interaction method is used to calculate the one-electron one-photon (OEOP) and less explored intense two-electron one-photon (TEOP) transitions from states of 1*s*2s3*s* configuration in Li-like ions with $12 \leq Z \leq 54$. The rates and energies are calculated using Multi Configuration Dirac-Fock wavefunctions in the active space approximation [1]. Special attention has been paid to elaborate the interplay between electron-electron correlation and higher order relativistic corrections on the line intensities. The TEOP transitions from the present three electron configuration and 2*s*3s configuration in He-like ions [2] are analyzed so as to understand the impact of K shell spectator vacancies on the transition rates. The strong influence of TEOP transitions in the accurate evaluation of level lifetimes is emphasized. Present results are compared with few available theoretical data [3].

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g-factor of middle-Z lithiumlike and boronlike ions

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Combined experimental and theoretical studies of the g factor of few-electron ions have resulted in the most accurate to date value of the electron mass [1] and can serve for an independent determination of the fine structure constant α [2, 3]. We present the improved theoretical values for the g factor of middle-Z lithiumlike and boronlike ions. Reevaluation of the higher-order many-electron contributions within the newly developed approach allows us to reach the uncertainty of the order of 10^{-9} for lithiumlike ions. Comparison with the recent measurements for lithiumlike silicon and calcium provides the most stringent to date test of the many-electron bound-state QED effects in the presence of magnetic field [4, 5, 6]. For boronlike ions, the rigorous evaluation of the correlation and QED corrections provides the theoretical predictions with the uncertainty of the order of 10^{-6}. The obtained results disagree with the ones of Ref. [7].

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The hyperfine-puzzle of strong-field bound-state QED

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A combined measurement of the ground-state hyperfine structure splitting in H-like and Li-like bismuth, the so-called specific difference

$$\Delta' E = \Delta E_{2s}^{\text{Li-like}} - \xi \Delta E_{1s}^{\text{H-like}},$$

was proposed to be ideally suited for a test of bound-state quantum electrodynamics (BS-QED) in strong fields, where a pertubative description of QED is no longer possible [1]. In this contribution, we report on our high-precision laser spectroscopy measurement in these few-electron systems, that has been carried out at the experimental storage ring (ESR) at the GSI Helmholtz-Center for Heavy Ion Research in Darmstadt [2]. The total accuracy of the hyperfine splitting determination was improved by more than an order of magnitude compared to previous measurements. Surprisingly, we found that the experimental value deviates by more than $7\,\sigma$ from the theoretical prediction, giving rise to the so-called *hyperfine puzzle* of BS-QED.

In addition to these results, we discuss possible explanations for the discrepancy and present the latest activities that have been carried out to provide a solution to this conundrum. In particular, we provide evidence that the observed discrepancy is caused by an inaccurate literature value of the nuclear magnetic moment μ_I of ^{209}Bi [3].

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Bound-electron g-factor and tetraquarks

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Recent progress in the theoretical prediction of the bound-electron g-factor will be reviewed, on the basis of [1]. In addition, an application of atomic variational calculations to studying exotic configurations of heavy quarks, so-called tetrons, will be presented [2].

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Hadronic atoms spectroscopy: overview and perspectives

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I shall review the results obtained in recent years in the experimental studies of exotic atoms, in particular on hadronic atoms.

I shall mostly focus on the studies of kaonic atoms performed at the DAFNE collider of LNF-INFN and at J-PARC in Japan, which have produced a valuable wealth of data which are used by theoreticians to better understand the QCD in non-perturbative sector, with implications going from particle and nuclear physics to astrophysics.

I shall present future perspectives, including ongoing programs, as SIDDHARTA-2 at DAFNE and E57 and E62 at J-PARC, as well as plans to measure sigmonic atoms transitions and to perform dedicated measurements of kaonic atoms to solve the "charged kaon mass inconsistency".

Hadronic atoms studies represent a unique opportunity to unlock the secrets of the QCD in the low-energy regime and to disentangle the role of strangeness in the neutron stars (equation of state of neutron stars).

FAMU: studies of the energy dependent transfer rate $\Lambda_{\mu p \to \mu O}$

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The main goal of the FAMU experiment is the measurement of the hyperfine splitting (hfs) in the 1S state of muonic hydrogen $\Delta E_{hfs}(\mu^- p)1S$ [1, 2, 3].

By measuring the transition $\Delta E_{hfs}(\mu^- p)1S$ in μp with $\delta\lambda/\lambda < 10^{-5}$, the experiment will provide the Zemach radius of the proton r_Z with high precision, disentangling in this way among discordant theoretical values. The level of discrepancy between values of r_Z as extracted from normal and muonic hydrogen atoms will be quantified, a result important also for the not yet explained anomalies on the charge r_{ch} radius of the proton. The physical process behind this experiment is the following: p are formed in a mixture of hydrogen and a higher-Z gas. When absorbing a photon at resonance-energy $\Delta E_{hfs} \approx 0.182$ eV, in subsequent collisions with the surrounding H_2 molecules, the μp is quickly de-excited and and accelerated by $\sim 2/3$ of the excitation energy. The observable is the time distribution of the K-lines X-rays emitted from the μZ formed by muon transfer $(\mu p) + Z \to (\mu Z)^* + p$, a reaction whose rate depends on the μp kinetic energy. The maximal response, to the tuned laser wavelength, of the time distribution of X-ray from K-lines of the $(\mu Z)^*$ cascade indicate the resonance.

During the preparatory phase of the FAMU experiment, several measurements have been performed both to validate the methodology and to prepare the best configuration of target and detectors for the spectroscopic measurement [4, 5, 6]. We present here the crucial study of the energy dependence of the transfer rate from muonic hydrogen to oxygen ($\Lambda_{\mu p \to \mu O}$), precisely measured for the first time.

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Measurement of the proton Zemach radius from the hyperfine splitting in muonic hydrogen atom

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The proton is a fundamental constituent of the matter. However, it has a complicated internal structure which is difficult to be fully understood. The internal structure of the proton is described by the electronic and magnetic form factors. The charge radius of the proton is defined by these form factors and has been determined experimentally. In recent years, a significant discrepancy between independent measurements of the proton charge radius was reported [1, 2]. This conflict is known as ”proton radius puzzle”. Even though various interpretations have been proposed, no definitive solution to the problem has been found yet. In order to shed some light on the puzzle, we proposed a new experiment to determine the proton Zemach radius which is defined as a convolution of the charge distribution with the magnetic moment distribution. The proton Zemach radius can be derived from the hyperfine splitting (HFS) in the muonic hydrogen atom. Figure 1 illustrates the experimental schematic. We aim to perform a laser spectroscopy of the muonic hydrogen HFS with the relative uncertainty of 1 ppm and obtain the proton Zemach radius with 1% precision.

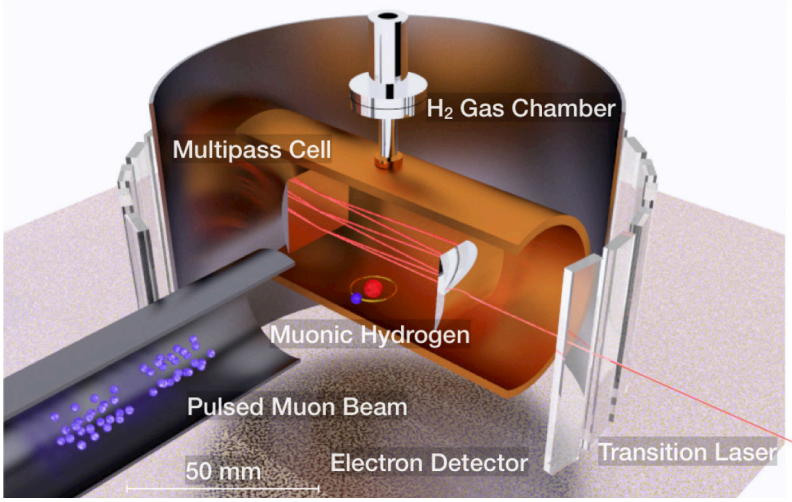

Figure 1: Experimental schematic. Pulsed negative muon beam irradiates the H_2 gas target. Muon is captured by the Coulomb field of the proton and forms a muonic hydrogen atom. The hyperfine transition between the spin singlet state and the triplet states is induced by a mid-infrared laser light. Electrons from muonic hydrogen decay are detected by the electron counter placed around the gas chamber.

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Higher-order finite-nuclear-size contributions in light muonic atoms

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We discuss the finite-nuclear-size contributions to the Lamb shift in a light muonic atom up to the order $\alpha^6 m$. The related corrections have a different Z dependence and different order in mR_N. The consideration is done within the external field approximation. We also found the leading logarithmic finite-nuclear-size contribution in the next order. It is of the order $\alpha(Z\alpha)^6 \ln^2(Z\alpha)(mR_N)^2 m$ and is comparable with some $\alpha^6 m$ finite-size corrections. A special attention is paid to higher-order effects in muonic hydrogen.

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 [1], the proton charge radius [2], and the fine-structure constant [3, 4]. It also sets constraints on new physics beyond the standard Model(BSM). High-precision spectroscopy of atomic helium, combined with ongoing theoretical calculations for the point nucleus may allow an alternative determination of the helium nuclear charge radius, which could be more accurate than from the electron scattering. Moreover, the comparison of results from electronic and muonic helium will provide a sensitive test of universality in the electromagnetic interactions of leptons.

The 2^3S-2^3P transition of He is particularly suitable for this purpose, because it is relatively sensitive to the nuclear charge radius and can be calculated within the QED theory up to $m\alpha^7$ order. These calculations will bring the theoretical accuracy to the 10-kHz level and may allow the determination of the helium nuclear charge radius with an accuracy of 10^{-3}.

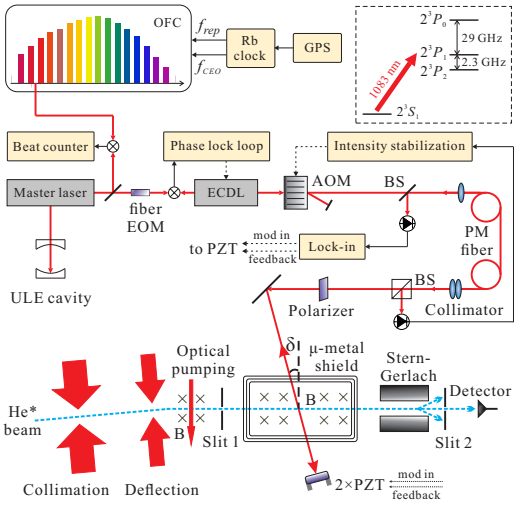

Figure 1: Schematic of the beam apparatus and the optical layout

Recently, We perform an laser spectroscopy measurement of the 2^3S-2^3P transition of ^4He in an atomic beam. The configuration of the experimental setup is shown in Fig.1. 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 $m\alpha^7$ corrections have been accomplished. This will enable a comparison of the r_{He} values obtained from electronic and from muonic helium in the future. Such a comparison will help to resolve the proton charge radius puzzle, while in the case of disagreement with muonic determination it will open a window for new physics beyond the standard Model by violation of the lepton universality in electro-magnetic interactions.

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Sub-kHz measurement of the 2 ^{3}S – 2 ^{1}S transition frequency in ^{4}He

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We have measured the transition frequency between the two metastable states of ^{4}He, 2 $^3S_1$ (lifetime 8 ks) and 2 $^1S_0$ (lifetime 20 ms), with 0.20 kHz accuracy (1.0×10^{-12} relative accuracy). Our result is almost a factor of ten more accurate than the previous result [1] and agrees within 2σ. The result connects orthohelium and parahelium tightly and constitutes the most accurate optical frequency measurement in the helium atom to date.

Our measurement is performed on a Bose-Einstein Condensate (BEC) of ^{4}He atoms in the 2 $^3S_1$ state, confined at a temperature of 0.2 μK in a crossed optical dipole trap (ODT). We have used an ODT near the 319.8-nm magic wavelength, minimizing AC Stark shifts in the transition. We measured this magic wavelength with 0.00015 nm accuracy and found very good agreement with calculations based on tabulated level energies and dipole matrix elements [2]. In the experiment we excite the 1557-nm transition with a telecom fiber laser, offset-locked to an ultrastable (~1 Hz) laser via a femtosecond frequency comb laser, realizing a 5 kHz laser linewidth over our 0.1 s interrogation time of the trapped atoms. We observe the transition (linewidth typically 10 kHz) counting the ions produced by Penning ionization of 2 ^{1}S atoms with 2 ^{3}S atoms in the trap. The excitation inside a BEC also causes a mean-field shift of the transition frequency, similar to the 1S–2S experiments in an atomic hydrogen BEC [3]. Varying the chemical potential we extract the *s*-wave singlet-triplet scattering length with 5% accuracy and find good agreement with a measurement of this scattering length performed in an ODT at 1.56 μm [4], however with much higher accuracy and now strongly disagreeing with a quantum chemistry calculation based on a complex potential of the 2 ^{1}S – 2 ^{3}S helium dimer.

Our new value of the transition frequency agrees very well with the most recent QED calculations, which have an accuracy of 0.8 MHz [5]. When we combine our new measurement with our earlier result on the same transition for ^{3}He, which 'only' has a 1.5 kHz accuracy [1], strong cancellation of QED terms in the isotope shift lead to a theoretical accuracy in the point-nucleus isotope shift of 0.19 kHz [5], which allows extraction of the difference in the squared nuclear charge radii for both isotopes, $\delta r^2 = r_3^2 - r_4^2$, with 0.007 fm^2 accuracy (6×10^{-3} relative accuracy). We hope to significantly improve on the isotope shift accuracy in the near future by measuring the ^{3}He transition in a magic-wavelength trap as well. Our present value for δr^2 still disagrees with δr^2 measurements from the isotope shift in the 2 ^{3}S – 2 ^{3}P transition, that also disagree among each other [6]. Comparison with δr^2 from μ-^{3,4}He$^+$ Lamb shift measurements at the Paul Scherrer Institute will reveal if there is also a helium nuclear size puzzle.

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The 413 nm tune-out wavelength for $2\,^3S_1$ state of helium as test of QED

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The tune-out wavelength is the wavelength at which the dynamic dipole polarizability vanishes. The 413 nm tune-out wavelength of the $2\,^3S_1$ state of helium is proposed as a non-energy test of quantum electrodynamic (QED) [1], which sparks great interest in high-precise measurement [2] and high-accuracy calculations of the tune-out wavelength of helium [3, 4]. So far, there exists 19 ppm discrepancy between the trapped-atom dynamics measurement of 413.0938(9stat)(20syst) nm [2] and the relativistic configuration-interaction (RCI) calculation of 413.0859(4) nm [3]. In present work we performed larger-scale RCI calculation based on the Dirac-Coulomb-Breit (DCB) equation with the mass shift operators included directly in the Hamiltonian. The advantage of this developed RCI method is that the finite nuclear mass and relativistic nuclear recoil corrections on the tune-out wavelength are taken into account self-consistently in DCB framework. The QED correction on the tune-out wavelength is also estimated. Our result of tune-out wavelength is 413.090 13(5) nm with an uncertainty of 0.12 ppm, which is more accurate than the experimental value from Ref. [2]. This work will motivate a future experimental campaign to seriously test QED at higher level of accuracy.

Contributions	λ_t (nm)
RCI	413.085 87(3)
α^3 QED without $\partial_\varepsilon^2 \ln k_0$	0.004 145 6(2)
α^3 QED from $\partial_\varepsilon^2 \ln k_0$	0.000 04(1)
α^4 radiative term	0.000 071 4(2)
Total	413.090 13(5)
Experiment [2]	413.093 8(9_{stat})(20_{sys})

Table 1: Comparison of the 413 nm tune-out wavelength for the $2\,^3S_1(M_J = \pm 1)$ state of ^{4}He.

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The construction of the low energy Li^+ source and the preliminary spectroscopy for the 1s2s ^3S - 1s2p ^3P transitions

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As the simplest system, Li^+ has significant application in verifying the quantum electrodynamics (QED) theory and determination of the fine-structure constant α, because the spectrum of Li^+ ion can be calculated accurately in theory [1-4]. We constructed a low energy Li^+ source by electron bombardment, and energy of the $^7Li^+$ ions is 500 eV (Fig. 1). The 1s2s ^3S -1s2s ^3P transitions of $^7Li^+$ are investigated by laser saturation spectroscopy on a low-energy Li^+ ion beam which radial Doppler broadening is optimized to 200 MHz, and the transition frequency is identified by Lamb dip (Linewidth ~ 40 MHz) (Fig. 2). Meanwhile, the laser frequency is measured by an optical frequency comb (FC8004, Menlo Systems GmbH). Hyperfine and fine structure splits can be derived from these transitions, in which most of the systematic frequency shifts are canceled. We are optimizing the stability of the laser and ion beam. The uncertainty of the hyperfine and fine structure splits is promising to less than 100 kHz.

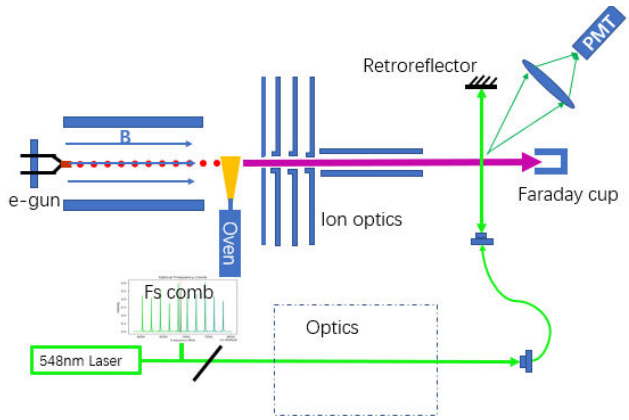

Figure1： the low energy Li^+ source and the schematic of the saturation spectroscopy

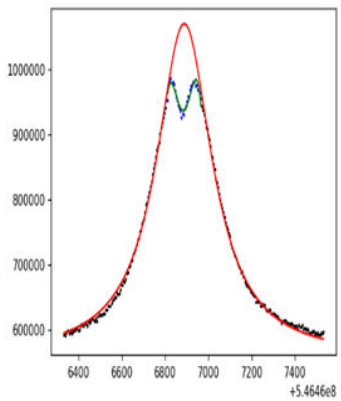

Figure2：Lamb dip of saturation spectroscopy

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CANNEX - A parallel plate approach to physics

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Since the discovery of accelerated cosmic expansion dark energy has evolved from a niche subject of cosmology to a focus topic of several related fields. Motivation is given by the cosmological constant problem, originating from the 120 order-of-magnitude discrepancy between actual measurements and the QED prediction for the cosmic vacuum energy density. Among the numerous theories aiming to explain dark energy, effective field theories implementing some kind of screening mechanism have become popular recently. The so-called 'chameleon' model introduces a scalar field whose interactions with ordinary matter depend on the local energy density. This variability allows the theory to be in agreement with all present observations but experimental tests have failed to completely exclude or find evidence for chameleon interactions. In 2010 it has been suggested that a precision measurement of the modulation of the force between macroscopic parallel plates with the pressure of an ambient gas could finally achieve this goal. Another problem related to vacuum energy is the Casimir effect. In MEMS, being widely used in industry and mobile devices, this effect is a major blocker of miniaturization. New geometric structures to overcome the problem are being developed but accurate measurements in geometries involving parallelism are required to verify design methods. A more fundamental problem in Casimir physics, being discussed already for two decades, is centered around the deep question if real and virtual photons behave in the same way. While experimental data clearly state that for virtual photons, dissipation at zero frequency has to be disregarded, for 'real' (thermal) photons, the situation is unclear. If real photons interact dissipatively while virtual ones don't this would be an indication for physics beyond the standard model at low energy. An unambiguous answer could be given by accurate force measurements at large separation - only possible using the parallel plate geometry. After a six-year construction phase the Casimir and Non-Newtonian force EXperiment (CANNEX), devised to detect sub-pN forces between macroscopic plane parallel plates, is starting to give first data. While the experiment is still in the prototype stage, its unique configuration could yield a wealth of metrological force data, answering long-standing questions in two different fields of physics. The present talk focuses on some of the physical questions that can hopefully be solved with CANNEX, the status of the experiment, and results of the very first force measurements between truly parallel macroscopic plates, obtained with the prototype.

Effects of spacetime topology and curvature on the resonance interatomic energy

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We study, using the formalism proposed by Dalibard, Dupont-Roc, and Cohen-Tannoudji [1], the resonance interatomic energy (RIE) of two identical two-level static atoms in a symmetric/antisymmetric entangled state, which are coupled to massless scalar fields, in a number of different spacetimes. We first show that the presence of a boundary in a flat Minkowski spacetime can dramatically modify the RIE of the two static atoms, resulting in an enhanced or weakened and even nullified RIE, as compared with that in the unbounded case (Fig. 1 for example); we then show that the RIE of the two atoms in the spacetime of a Schwarzschild black hole can be sharply affected by the spacetime curvature on one hand, but on the other hand it is surprisingly undisturbed by the Hawking radiation of the black hole [2]; we finally show that (Fig. 2 for example) the nontrivial topological structure of the spacetime with an infinite and straight cosmic string imprints on the RIE of the two static atoms, making it behaves in a manner very similar to that near a perfectly reflecting boundary in a flat Minkowski spacetime [3].

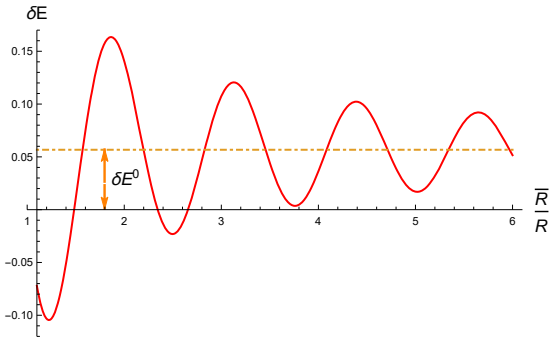

Figure 1: The RIE (δE) of two static atoms near a perfectly reflecting boundary in a Minkowski spacetime. We denote the RIE of two atoms in a free space, the interatomic separation and the separation between an atom and the image of another atom with δE_0, R and $\bar{R}$ respectively. The ordinate is of unit $\mp\frac{\lambda^2\omega_0}{16\pi}$.

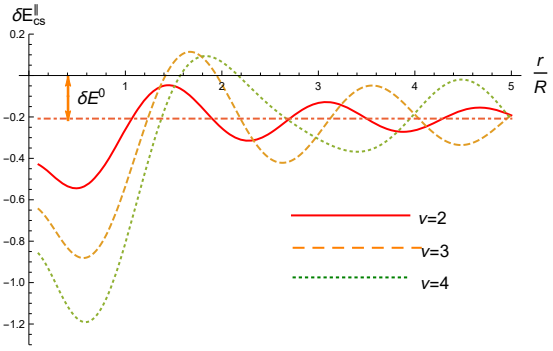

Figure 2: The RIE of two static atoms aligned with their separation parallel to an infinite and straight cosmic string. We denote the interatomic separation and the atom-string separation by R and r respectively, and choose $\omega_0 R = 2$. The ordinate is of unit $\mp\frac{\lambda^2\omega_0}{16\pi}$.

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First search for invisible decays of ortho-positronium confined in a vacuum cavity

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The experimental setup and results of the first search for invisible decays of ortho-positronium (o-Ps) confined in a vacuum cavity are reported. No evidence of invisible decays at a level $\mathrm{Br}\,(\text{o-Ps} \to \text{invisible}) < 5.9 \times 10^{-4}$ (90 % C. L.) was found. This decay channel is predicted in Hidden Sector models such as the Mirror Matter (MM), which could be a candidate for Dark Matter. Analyzed within the MM context, this result provides an upper limit on the kinetic mixing strength between ordinary and mirror photons of $\varepsilon < 3.1 \times 10^{-7}$ (90 % C. L.). This limit was obtained for the first time in vacuum free of systematic effects due to collisions with matter.

The experimental setup will also allow us to measure the o-Ps decay rate. Currently, the experimental uncertainty of the o-Ps decay rate is at 140 ppm precision; this exceeds the theoretical accuracy (1 ppm level) by two orders of magnitude. We propose a method that relies on the o-Ps confinement cavity and the granularity of the surrounding calorimeter to subtract the time dependent pick-off annihilation rate of the fast backscattered positronium from the o-Ps decay rate prior to fitting the distribution. Therefore, this measurement will be free from the systematic errors present in the previous experiments and thus could reach the ultimate accuracy of a few ppm level to confirm or confront directly the higher order QED corrections.

New Atomic Probes for Dark Matter and Neutrino-Mediated Forces

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Low-mass bosonic dark matter particles produced after the Big Bang may form an oscillating classical field, which can be sought for in a variety of low-energy laboratory experiments based on spectroscopic, interferometric and magnetometric techniques, as well as in astrophysical phenomena. Dark bosons can also mediate anomalous fifth forces between ordinary-matter particles. Recent measurements in atoms and astrophysical phenomena have already allowed us to improve on existing constraints on a broad range of non-gravitational interactions between dark bosons and ordinary-matter particles by many orders of magnitude (up to 15 orders of magnitude in the case of low-mass dark matter). Additionally, existing atomic and nuclear spectroscopy data have allowed us to improve limits on long-range neutrino-mediated forces by 18 orders of magnitude.

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Quantum metrology – in search of dark matter

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This is a Precision measurement plays an important role in unveiling new physics by probing beyond the known boundaries of knowledge. In a similar footing, it has a wide range of application in trade and commerce. From fundamental physics viewpoint, the Standard Model (SM) of particle physics though considered to be the most celebrated model in physics is known to have shortcomings as is evident from numerous experimental findings. Precision measurements with simple atomic systems provide the opportunity to explore the possible deviations from the SM. The limit to the uncertainty of any frequency measurement is given by the Heisenberg limit. However as will be shown here, using a time dependent Hamiltonian it is possible to surpass this limit. Using, this technique, a trapped single atomic probe provides a weak limit of the coupling of a electron spin to a certain type of dark matter candidate. Possible new experiments can further improve the limit for more assertive searches.

Toward a determination of the proton-to-electron mass ratio from a Lamb-dip measurement of HD

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Precision spectroscopy of the hydrogen molecule is a test ground of quantum electrodynamics (QED), and may serve for determination of fundamental constants. Using a comb-locked cavity ring-down spectrometer [1], for the first time, we observed the Lamb-dip spectrum of the R(1) line in the overtone of HD. The line position was determined with a precision of 90 kHz, which is the most accurate transition ever measured for the hydrogen molecule. Moreover, from calculations including QED effects up to the order $m_e\alpha^6$ [2], we obtained predictions for this R(1) line as well as for the HD dissociation energy, which are less accurate but signaling the importance of the complete treatment of nonadiabatic effects. Provided that the theoretical calculation reaches the same accuracy, the present measurement will lead to a determination of the proton-to-electron mass ratio with a precision of 1.3 parts per billion.

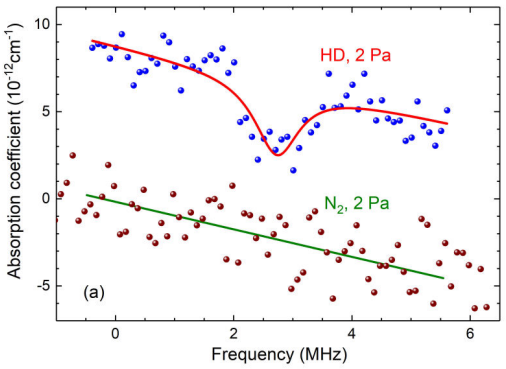

Figure 1: Lamb dip spectrum of the R(1) 2-0 line of HD

	D_0, (0,0)	2-0, R(1)
$E^{(2)}$	36406.510839(1)	7241.846169(1)
$E^{(4)}$	-0.531325(1)	0.040719
$E^{(5)}$	-0.1964(2)	-0.03743(4)
$E^{(6)}$	-0.002080(6)	-0.000339
$E^{(7)}$	0.00012(6)	0.000021
E_{FS}	-0.000117	-0.000021
Total	36405.7810(5)	7241.84912(6)
Expt.	36405.78366(36) [3]	7241.849386(3)
Diff.	0.0026	0.00027

Table 1: Calculated and experimental energies of HD (unit: cm^{-1}).

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Accurate spectroscopy of deuterium molecule

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The accuracy of the molecular spectroscopy on weak transitions (too weak to saturate) in molecules which cannot be cooled and trapped, is presently limited to the sub-megahertz level, without clear perspectives for further substantial improvements. We demonstrate a new method with the potential to achieve kilohertz-level accuracy. We bring the Doppler-regime measurements into the high-pressure region, where the signal-to-noise-ratio is much higher. The expected deterioration of accuracy by collision-induced systematics [1] is mitigated with *ab initio* line-shape and quantum scattering calculations [2]. We test our approach on a case of weak quadrupole transition in D_2, which is a benchmark system for testing quantum electrodynamics in molecules. We validate our methodology at the 400 kHz level by comparing our results with the best previous determination [3]. We demonstrate that our approach achieves higher accuracy despite much milder experimental requirements (in Ref. [3], the effective optical path was 20 times longer). For the same experimental apparatus, the accuracy of our approach will be at least one order of magnitude better. For the first time, we applied *ab initio* quantum scattering calculations to address the collisional line-shape effects [4, 5] in ultra-accurate spectra analysis collected at high pressures. The experimental and theoretical values of the 2-0 S(2) line position in D_2 reported here constitute the most precise comparison of the experimental and theoretical *ab initio* determinations of rovibrational splitting for any neutral molecule. We observe a 3.4σ discrepancy, which, together with previously reported discrepancies [6], indicates that the theoretical accuracy is underestimated because of the uncalculated terms.

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Improved determination of the dissociation energy of H_2

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The dissociation energy (D_0) of H_2 is a benchmark value in quantum chemistry, with recent QED calculations now approaching accuracies achievable in simple atoms. Precise measurement of the *GK-X* molecular transition, in combination with other precision measurements, provides a determination of D_0. The *GK-X* transition is excited through Doppler-free two-photon spectroscopy using 179-nm radiation, based on frequency up-conversion using a special KBBF crystal. The optical frequency of the fundamental (716 nm), which is the output of a narrowband pulsed Ti:Sa laser system, is locked to a frequency comb. This enables accuracies of the *GK-X* transition to a few parts in 10^{10} or MHz level, leading to an order-of-magnitude improvement for D_0. The comparison of this accurate experimental result with the best calculations may provide a test of the Standard Model of Physics.

Nuclear Spin-Independent Effects of Parity NonConservation in Molecule of Hydrogen

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Theoretical study of discrete symmetry (e.g. spatial parity $\mathcal{P}$) violation effects in atomic and molecular systems plays a key role in developing theories and models of fundamental interaction physics. In all atomic experiments only the $\mathcal{P}$-odd electron-nucleus (*e*-N) interaction was observed since it is enhanced in heavy atoms, while the $\mathcal{P}$-odd electron-electron (*e*-*e*) interaction is negligible [1]. In 1977 it was proposed to observe the effect of optical rotation on oxygen molecule [2]. According to very rough estimates in this case the $\mathcal{P}$-odd *e*-*e* interaction effect should prevail over the $\mathcal{P}$-odd *e*-N one. The idea was that all electrons of a molecule involved in formation of the chemical bond are concentrated in the region between the nuclei, so there should not arise additional smallness in the matrix element of the $\mathcal{P}$-odd *e*-*e* interaction, which is present in atoms for that effect. It follows from our recent calculations via coupled cluster method [3] that for O_2 the $\mathcal{P}$-odd *e*-*e* interaction is suppressed compared to the $\mathcal{P}$-odd *e*-N one and, in principle, cannot be separated out in this case. Note also that this suppression in O_2 is less than the one in an atom with the same nuclear charge.

This contribution is devoted to the description and the calculation of the $\mathcal{P}$-odd effects in diatomic homonuclear molecule of parahydrogen H_2. For this purpose the M1 transition between the states with the same rotational number of the vibrational $v = 1 \leftarrow 0$ band in the H_2 ground electronic $^1\Sigma_g^+$ state [4] is considered. It is shown that in this case the effects of the $\mathcal{P}$-odd *e*-*e* and *e*-N spin-independent interactions are of the same order of magnitude. H_2 molecule is therefore the first example of atomic system where the *e*-*e* PNC interaction can be directly observed. Since the constants of the *e*-N PNC interaction were already accurately measured in atomic experiments, the *e*-*e* PNC interaction constant also can be extracted from these experiments. In all other atoms and molecules the *e*-*e* PNC interaction is usually deeply screened by the *e*-N interaction. Then the evaluations of the PNC effect in the parahydrogen molecule H_2 may acquire another important sense. The parahydrogen molecule H_2 is the unique atomic system also because in this molecule the *e*-*e* and *e*-N weak interaction constants are the same. Then a moment's consideration shows that the PNC experiments with H_2 molecule may become a source of the most accurate values for the Weinberg's angle.

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Measurement of the Electric Dipole Moment of the ^{129}Xe Atom

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Precision measurements of fundamental symmetry violations in atoms can be used as a test of the Standard Model of elementary particles and to search for new physics beyond it. Electric Dipole Moments (EDMs) of fundamental or composite particles are excellent candidates to look for new sources of violation of CP symmetry. We describe a setup to measure the CP violating permanent EDM of the neutral ^{129}Xe atom. Our goal is to improve the present experimental limit ($d_{Xe} < 3 \cdot 10^{-27}$ ecm [1]). The experimental approach is based on the free precession of nuclear spin polarized ^{3}He and ^{129}Xe atoms in a homogeneous magnetic guiding field of about 400 nT [2, 3]. A finite EDM is indicated by a change in the precession frequency as an electric field is periodically reversed with respect to the magnetic guiding field. To render the experiment insensitive to fluctuations and drifts of the magnetic guiding field, the principle of co-magnetometry is used: Two different spin species are located in the same volume (hyperpolarized ^{129}Xe and ^{3}He gas in the same measurement cell). The experiment benefits strongly from long spin-coherence times of several hours [4]. We discuss the methods of data evaluation and analyze different sources of noise and systematic effects, and the sensitivity of the ^{129}Xe EDM to underlying sources of CP violation on the level of elementary particle interactions. We report on technical improvements and first experimental results achieved within the MIXed collaboration.

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Atomic parity violation in ytterbium

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In the study of electroweak interactions, atomic parity violation (APV) experiments form a powerful tool, providing valuable information about the Standard Model and low-energy nuclear physics. Ytterbium is an excellent system for such studies, due to its strong APV effect (largest effect observed in any atomic system to date) and the availability of many stable isotopes. This brings within reach the possibility to perform high-precision measurements of the isotopic dependence of the effect, which would serve as a probe of the neutron skin variation among these different isotopes of the ytterbium nuclei. In addition, a determination of the nuclear spin-dependent contributions to the APV effect would be an observation of the nuclear anapole moment, and would yield information about nucleon-nucleon weak meson couplings.

Our programme in ytterbium parity violation in Mainz has reached in early 2018 its first milestone, namely the observation for the first time, of the isotopic variation of the APV effect, as predicted by the electroweak theory. We will present the result of these measurements, and discuss future prospects for determining nuclear spin-dependent APV effects as well as neutron distributions in ytterbium.

Precise study of heavy-atom compound electronic structure to extract fundamental properties of electron and nuclei

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Search for the effects of violation of time-reversal and spatial parity symmetries of fundamental interactions is of key importance to test extensions of the standard model. The interactions can lead to nonzero value of permanent electric dipole moment of the electron (eEDM), nuclear magnetic quadrupole moment (MQM), nuclear Schiff moment (NSM), etc. Heavy-atom compounds are very promising systems to search for these fundamental characteristics. However, the interpretation of experiments in terms of eEDM, MQM, NSM, etc. requires knowledge of the magnitude of corresponding molecular parameters such as effective electric field acting on the eEDM which cannot be measured and this is the task for modern relativistic quantum chemistry methods.

We use a method, which allows one to significantly simplify the relativistic treatment of such characteristics. This approach includes relativistic correlation calculation of valence electronic structure using the generalized relativistic pseudopotential approach followed by the non-variational restoration of four-component electronic structure in the vicinity of heavy-atom nucleus. We show [1] that this method can be efficiently combined with the direct 4-component Dirac-Coulomb-Breit approach to consider contributions of the (excluded from pseudopotential calculations) inner-core electrons, remove uncertainties due to approximate restoration procedure and treat high order correlation effects up to the coupled cluster method with single, double, triple, and perturbative quadruple amplitudes. In the report the status [1] and applications of the method to the atoms [2], molecules [1,3,5] and solids [4] most actual to search for the New physics – ThO, HfF^+, Fr, ThF^+, TaN, PbF, $PbTiO_3$, etc. are given. Calculation [5] is required for exhaustive interpretation of the experimental data by Cornell/Ye group [6].

We also show that precise relativistic methods of electronic structure calculation of molecules (finite field coupled cluster approaches) can be used to accurately extract nuclear magnetic moments from NMR experiments [7]. Applications of such methods allowed us to resolve [7] recently-established "hyperfine puzzle" [8].

The code to compute electric field gradients was developed with the support of the Russian Science Foundation grant (Project No. 14-31-00022). Atomic and molecular studies were supported by the RFBR Grant #16-32-60013 mol__dk and President of Russian Federation grant #MK-2230.2018.2.

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Precision Measurement of the Isotope Shift in Neutral Boron

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The 2p-3s ground-state transition in the atomic five-electron system of neutral Boron has been measured using Resonance Ionization Mass Spectroscopy (RIMS). A stable Boron atom beam was overlapped perpendicular with two laser beams. While one laser was frequency-scanned over the atomic resonance, it was simultaneously monitored with a frequency comb, providing an accurate reading for the absolute frequency. The second laser was used for non-resonant ionization out of the previously excited 3s state. Ions were extracted from the ionization region and guided into a quadrupole mass spectrometer and finally detected by a channeltron. The mass selection provided almost background-free single-ion detection. The acquired spectra allowed us to extract absolute transition frequencies and the isotope shift of ^{10}B and ^{11}B with high precision.

The resulting values show significant improvements in precision compared to previously published values. With these results, the five-electron system wave function calculations which were carried out recently [1] can be tested. In particular, they allow to extract the change in mean-square nuclear charge radius from the isotope shift in a nuclear model-independent way. This observable can be tested against recent ab-initio nuclear model calculations as well as experimental results for stable boron.

Furthermore, we strive to extend these isotope shift measurements along the boron isotopic chain to the short-lived (770 ms) proton-halo candidate ^{8}B. The most decisive observable to confirm its halo character, the nuclear charge radius, can be extracted from such measurements.

In this presentation, the results of the offline experiment will be presented. Also, a status and outlook of our efforts towards the measurement of the ^{8}B mean-square nuclear charge radius at Argonne National Laboratory will be given.

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Leptonic and semi-leptonic decays of charmed mesons at BESIII

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The BESIII experiment at the BEPCII collider accumulated 2.93 and 3.19 fb^{-1} e^+e^- collision samples at the center-of-mass energies of 3.773 and 4.178 GeV, respectively. They are all the world's largest ones to date. Using these data samples, we have studied the purely leptonic decays $D^+_{(s)} \to \ell^+\nu_\ell$, and the semi-leptonic decays of $D^0 \to K(\pi)^- e^+ v_e$, $K(\pi)^-\mu^+ v_\mu$, $D^+ \to \bar{K}^0(\pi^0)e^+v_e$, $\bar{K}^0(\pi^0)\mu^+v_\mu$ and $D_s^+ \to K^{(*)0}e^+v_e$. We will report the improved measurements of the branching fractions of these decays and the CKM matrix elements $|V_{cs(d)}|$, the $D^+_{(s)}$ decay constants, the form factors of $D^+_{(s)}$ semi-leptonic decays. These results are important to calibrate the LQCD calculations of $D^+_{(s)}$ decay constants and form factors and to test the CKM matrix unitarity.

Charmonium(-like) spectroscopy with BESIII

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After a short review of the overall physics program of BESIII and the key features of the BEPCII collider and BESIII detector, I will present some of the recent highlights of the charmonium(-like) spectroscopy program of BESIII. The results include measurements of radiative and hadronic decays of several charmonium(-like) states below and above the open-charm production threshold. The ultimate aim is to provide data to study the dynamics of the strong interaction in the confinement region and to understand the nature of the recently discovered XYZ states. In this talk, I will discuss on what has been learned so far and what the future perspectives could be in this field of hadron physics.

The $\mu\mu$tron physics program

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The construction of the low-energy e^+e^- collider ($\mu\mu$tron) operating near the muon-pair production threshold begins in 2018 at BINP (Novosibirsk). The collider parameters and configuration (a luminosity of 8×10^{31} cm^{-2}c^{-1}), an center-of-mass energy spread of 400 keV, and beams collision with a large crossing angle) allow to perform experiments on study of dimuonium properties. The dimuonium is the $\mu^+\mu^-$ bound state that has not yet been observed. At $\mu\mu$tron it will be possible to detect about 40 thousand dimuonium atoms per year (10^7 s). In this report we describe the physics program of $\mu\mu$tron.

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Muon (g-2) and measurement of hadronic cross-sections at CMD-3

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Precise measurement of the muon anomalous magnetic moment $a_\mu = (g_\mu - 2)/2$ provides a stringent test of the Standard Model and a tool for a search of physics beyond the Standard Model at the laboratory. There is a long-standing 3–4 standard deviations difference between the result of the latest measurement of a_μ in Brookhaven National Laboratory [1] and the Standard Model prediction of a_μ [2, 3]. In 2018 a new experiment E989 [4] to measure a_μ has started data taking at Fermilab with an ultimate goal of 4-fold improvement in precision compared to the BNL measurement.

There are world-wide efforts to improve the accuracy of the Standard Model prediction of a_μ to match the expected precision of the Fermilab measurement. The dominant contribution to the theoretical error comes from the evaluation of the hadronic contribution. While a lattice-based approach to calculate the hadronic contribution from the first principles shows great progress over last years, the best precision is still achieved with the traditional dispersive approach, based on the integration of the measured total cross-section of $e^+e^- \to hadrons$. The calculation is heavily dominated by low-energy data, in particular, by data at $\sqrt{s} < 2$ GeV.

The CMD-3 experiment at the VEPP-2000 collider [5] in Novosibirsk carries out the comprehensive program of measurements of the exclusive cross-sections $e^+e^- \to hadrons$ in the energy range from the threshold to $\sqrt{s} < 2$ GeV. The first round of data taking in the whole available energy range was done in 2011-2013 . After a three-year break for collider and detector upgrades, data taking resumed in 2017.

We'll present the overview of the field and the status and current results from the CMD-3 experiment.

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Collider experiment SND and Precision Physics with hadronic e^+e^- cross sections

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Spherical neutral detector (SND) is an experiment for e^+e^- annihilation study at moderate energies 0.2-2 GeV. The light quark anti-quark bound states are main subject of study at these energies. The quark anti-quark states express themselves as resonances in the $e^+e^- \rightarrow$ hadronic cross sections. The hadronic cross sections could be recalculated to hadronic vacuum polarization (HVP). The Standard Model predictions today are limited by HVP which is not calculable with modern Quantum chromo dynamics theory. In this talk we present the review of the hadronic cross sections measurements at SND and some new measurements: $e^+e^- \rightarrow \pi^+\pi^-$, $\pi^0\gamma$, K^+K^-, $\omega\pi^0$, $K^+K^-\eta$, $\pi^+\pi^-\eta$, $K_sK_L\pi^0$, $\pi^+\pi^-\pi^0\eta$, $\omega\pi^0\eta$ e.t.c.

$\mathcal{P}$,$\mathcal{T}$-odd Faraday effect in heavy neutral atoms

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Theoretical study of discrete symmetry (e.g. spatial parity $\mathcal{P}$ and time-reversal parity $\mathcal{T}$) violation effects in atomic systems plays an important role in developing theories and models of fundamental interaction physics. The existence of the $\mathcal{T}$-noninvariant interactions in the nature is one of the most important fundamental problems which has to be solved by the modern physics. The $\mathcal{CP}$-violation ($\mathcal{C}$ - charge conjugation) discovered in [1] in the exotic reaction with K-mesons means, according to the $\mathcal{CPT}$-theorem that such interactions in principle exist. However a search for the more universal $\mathcal{T}$-violating interactions has been continued from 1950 up to now without success.

This contribution is devoted to the proposal to observe the $\mathcal{P},\mathcal{T}$-odd Faraday effect, i.e. rotation of the polarization plane of the light propagating through a medium in presence of an electric field in the intra-cavity absorption spectroscopy (ICAS) experiments [2]. The $\mathcal{P},\mathcal{T}$-odd Faraday effect may be caused by $\mathcal{CP}$ violation within the Standard Model. It is demonstrated that the observation of the $\mathcal{P},\mathcal{T}$-odd Faraday effect may compete with the observation of the $\mathcal{P},\mathcal{T}$-odd electron spin rotation in an external electric field which provides now the most stringent bounds for the $\mathcal{P},\mathcal{T}$-odd effects in atomic physics. We revisit the $\mathcal{P}$,$\mathcal{T}$-odd Faraday effect in view of a serious progress in the ICAS made during the last few decades [3]-[5]. For the Faraday rotation (ordinary or $\mathcal{P}$,$\mathcal{T}$-odd) the maximum of the effect coincides with the maximum of absorption what prevents usually the work off-line and employment of the large optical path length. However our proposal is based on working off-resonance using second Faraday rotation maximum existing both for the ordinary and $\mathcal{P}$,$\mathcal{T}$-odd Faraday effects. This would allow to employ very large optical path length (up to hundred kilometres) corresponding to the recent ICAS experiments and greatly enhance the $\mathcal{P}$,$\mathcal{T}$-odd Faraday rotation signal. Here we present the accurate calculations and a detailed analysis of the possible ICAS-type experiment. The calculations are performed for the heavy metal atoms Cs, Tl, Pb, Bi where the $\mathcal{P}$,$\mathcal{T}$-odd effects are most pronounced. The results of the calculations demonstrate that with that large optical path length the ICAS experiments will be able to fix the possible $\mathcal{P}$,$\mathcal{T}$-odd effects at the level several orders of magnitude lower than the other most advanced modern experiments.

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Nonadiabatic rotational states of H_2, HD, and D_2

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We present a new computational method for the determination of energy levels in four-particle systems like H_2, HD, D_2, HeH^+, and Ps_2 using explicitly correlated exponential basis functions and analytic integration formulas. In solving the Schrödinger equation, no adiabatic separation of the nuclear and electronic degrees of freedom is introduced. We provide formulas for the coupling between the rotational and electronic angular momenta, which enable calculations of arbitrary rotationally excited energy levels. To illustrate the high numerical efficiency of the method, we present results for various states of the hydrogen molecule. The relative accuracy to which we determined the nonrelativistic energy reached the level of 10^{-12}–10^{-13}, which corresponds to an uncertainty of 10^{-7}–$10^{-8}\,\mathrm{cm}^{-1}$.

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Relativistic corrections for the ground state of the hydrogen molecule

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The Schrödinger equation for the ground state of the hydrogen molecule is solved by the Rayleigh-Ritz variational method in Hylleraas coordinates without using the Born-Oppenheimer approximation. The non-relativistic energy eigenvalue converges to $-1.164\,025\,030\,4(5)$ a.u.. Then the leading order relativistic corrections (including the mass-velocity, Darwin, orbit-orbit, and spin-spin terms) and the relativistic recoil terms are calculated by perturbation method. Together with the QED corrections and higher-order corrections calculated by M. Puchalski, J. Komasa, and K. Pachucki [1], we obtain the dissociation energy of the hydrogen molecule $D_0 = 36\,118.069\,47(47)$ cm^{-1}, which agrees with the recent experimental results $36\,118.069\,62(37)$ cm^{-1} [2] and $36\,118.069\,45(31)$ cm^{-1} [3].

Table 1: The non-relativistic energy eigenvalue, the α^2 correction, and the α^2 contribution to the dissociation energy for the ground state of the hydrogen molecule.

Basis size	Non-relativistic energy (in a.u.)	α^2 correction (in 10^{-5} a.u.)	α^2 contribution to the dissociation energy (in cm^{-1})
256	–1.163 966 582 92	–1.088 999 4	–0.531 751
500	–1.164 014 701 97	–1.091 203 3	–0.526 914
912	–1.164 022 742 55	–1.090 704 3	–0.528 009
1570	–1.164 024 408 23	–1.090 057 1	–0.529 429
2570	–1.164 024 831 12	–1.089 629 1	–0.530 369
4050	–1.164 024 974 62	–1.089 440 2	–0.530 783
6150	–1.164 025 011 35	–1.089 361 0	–0.530 957
9070	–1.164 025 022 86	–1.089 315 7	–0.531 056
13020	–1.164 025 027 14	–1.089 288 1	–0.531 117
18270	–1.164 025 028 91		
25100	–1.164 025 029 71		
33870	–1.164 025 030 10		
Extrap.	–1.164 025 030 4(5)	–1.089 24(5)	–0.531 21(10)

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Precision Tests of Fundamental Interactions with Ion Trap Experiments

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Single particles in traps allow for clean investigations of basic interactions and also for the determination of fundamental constants. This has been demonstrated by investigations of Quantum Electrodynamics (QED) with respect to the g-factor of the free electron [1] and of hydrogen-like or lithium-like ions [2 - 4], which form the most precise determinations of the fine-structure constant and of the mass of the electron, respectively. Ion traps are also suitable for the study of the interaction of atomic ions with high-intensity laser radiation [5]. The trapping of hydrogen-like heavy ions up to uranium is possible at the heavy-ion accelerator at GSI with stripping and post-deceleration. At the HITRAP facility at GSI, the final stage for deceleration and trapping of bare and hydrogen-like heavy ions up to uranium has been commissioned. After stripping at energies of a few 100 MeV/u, the ions are decelerated down to 4 MeV/u in the Experimental Storage Ring (ESR) and further down to 6 keV/u by a combination of an IH and a RFQ structure operating as decelerators. Finally, the ions will be captured and cooled down to cryogenic temperatures in a Penning trap by means of electron cooling and resistive cooling. From this trap, they can be extracted and used for experiments. With this novel technique of deceleration, trapping and cooling of highly charged ions, atomic physics studies on slow highly charged ions up to uranium U^{92+} interacting with photons, atoms, molecules, clusters, and surfaces will be performed. In addition to collision studies, high-accuracy atomic physics experiments on trapped highly charged ions will be a significant part of the atomic physics program of the HITRAP facility. At the upcoming Facility FAIR, the HITRAP facility will form an integral component of both the SPARC as well as the FLAIR Collaborations.

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The relativistic and radiative corrections to the polarizability of hydrogen-like atoms

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The polarizability in atomic physics is important to determining the frequency standard [1], magic wavelengths and the tune-out wavelengths [2,3] of the atom in the optical lattice clock. It is also used to calculating the long-range interactions between atoms [4] in the cold atom research. However the higher order corrections are still researched inadequately [1,5]. In this work, starting from the relativistic polarizability of the Hydrogen-like atoms, we derive the operators of the nonrelativistic leading term and first order perturbation term: relativistic corrections and radiative corrections by applying Nonrelativistic Quantum Electrodynamic approach[6,7]. These correction are the dynamical parts, which dependent on the electric field frequency. The Bethe-logarithm-like correction is also obtained. This study can be helpful in our next step research about blackbody radiation contribution in atomic system, which is based on our previous study [8].

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Precision x-ray spectroscopy of the 1s Lamb shift in high-Z hydrogen-like systems

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The study of the 1s Lamb shift in hydrogen-like systems represents one of the most stringent tests of quantum electrodynamics (QED) for the most fundamental atomic systems. Due to the strong dependence of the Lamb shift on the nuclear charge Z, it is of high interest to test the predictions of QED in the regime of very strong electric fields, such as in hydrogen-like gold (Au^{78+}) or uranium (U^{91+}), where approximations relying on $\alpha Z \ll 1$ are not applicable. The present contribution will focus on most recent efforts with respect to high-precision Lamb shift studies in high-Z systems at GSI, Darmstadt.

After several experiments on the 1s Lamb shift in U^{91+}, conducted with conventional semiconductor detectors [3], the twin crystal spectrometer FOCAL has been developed [4] which is the result of a well-balanced trade-off between a high resolving power and detection efficiency. Namely, an acceptable efficiency is needed to operate the crystal spectrometer at an ion storage ring with a luminosity which is low compared to other high intensity x-ray sources like synchrotrons or nuclear reactors. The outcome of the first beam time using the complete two-arm FOCAL spectrometer will be presented, see Fig. 1. In addition, the development of microcalorimeters for the x-ray regime, that combine the high resolution typical for crystal spectrometers with the good efficiency of conventional solid state detectors, is expected to open a promising route for precision spectroscopy in high-Z systems. Here, we will discuss recent test measurements with the maXs prototype detector [5] as depicted in Fig. 2.

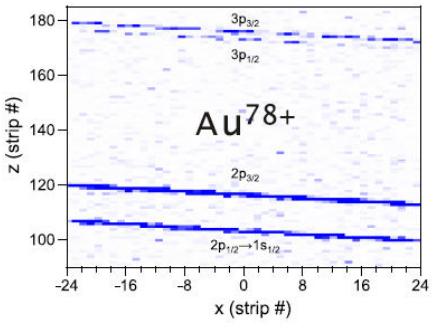

Figure 1: X-ray spectrum of hydrogen-like gold as recorded by a position sensitive detector after being dispersed by the FOCAL crystal. The lines correspond to the Lyman-α and -β transitions in Au^{78+}.

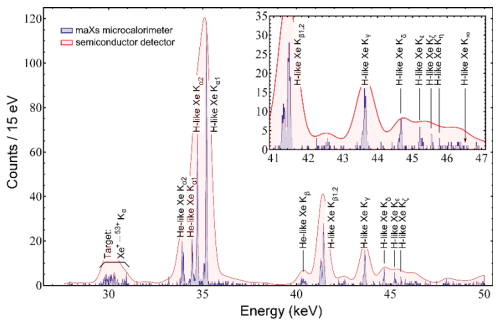

Figure 2: X-ray spectrum from the collision of a Xe^{54+} ion beam and a Xe gas target. The Doppler-shifted Lyman series of Xe^{53+} and Xe^{52+} are clearly visible. Centered around 30 keV one can see the K-lines of differently charged Xe ions from the target gas.

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High-precision Ramsey-comb spectroscopy in the XUV spectral range for tests of bound-state QED and the proton radius

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High-precision spectroscopy of simple atoms and molecules set the benchmark for tests of bound-state Quantum Electrodynamics (QED). Especially atomic hydrogen has served as a model system, and experimental efforts have lead to a measured 1S-2S transition frequency with a relative accuracy of 10^{-15} [1]. In order to improve the theoretical description of this system, the proton charge radius (r_p) was extracted from the measured Lamb shift in muonic hydrogen with a 10 times higher accuracy compared to previous determinations from electronic systems. This measurement, however, also shows a 5.6σ discrepancy with CODATA-2014 and this is now well known as the *proton radius puzzle* [2, 3]. Recent developments in this field have made matters even more confusing. The proton radius extracted from the measured 2S-4P transition frequency in electronic hydrogen agrees well with the muonic value [4], while a recent measurement of the 1S-3S transition frequency results in a value which coincides with CODATA-2014 [5]. Efforts are now being made to resolve this problem, using different systems. Therefore, our goal is to measure the 1S-2S transition in singly-ionized helium at 30 nm. This system is more sensitive to nuclear charge effects and the result can be compared directly with measurements conducted in muonic-He^+. Also, combining the expected more accurate determination of the nuclear charge-radius of the α-particle from the muonic-He^+ measurement with high accuracy spectroscopy of the 1S-2S transition in He^+, results in an even more stringent test of bound-state QED [6].
To pursue this goal we recently have developed the Ramsey-comb spectroscopy (RCS) method, which combines high-power amplified frequency comb laser pulses with high-precision frequency metrology. This enabled us to perform precision measurements in molecular hydrogen at deep ultra-violet wavelengths, demonstrating that RCS is very suitable for combining efficient frequency up-conversion with high-precision spectroscopy [7]. Moreover, systematic shifts due to the ac-Stark effect or chirp are greatly suppressed. We are currently extending this technique to the vacuum-UV and extreme-UV wavelength range using High-Harmonic Generation (HHG). A 3 meter long vacuum system was designed and constructed for this, and the latest results show that we have a refocused diffraction limited XUV beam ($\lambda < 50$ nm). We are currently testing RCS with HHG on the $5p^6 \rightarrow 5p^5 6d[1/2]_0$ transition in xenon at 113 nm (7th harmonic of 790 nm). With this measurement we can characterise the phase-shift induced by the HHG process and the quality of our XUV-beam, which is of great importance for the experiment in He^+.

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The next generation of laser spectroscopy experiments of light muonic atom

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Simple muonic atoms have been proven to be of particular interest for studies of nuclear properties, such as the charge and Zemach radii, and the nuclear polarizabilities. It has been found that the proton [1] and deuteron [2] charge radii extracted from muonic atom spectroscopy deviate by about 5σ from the present CODATA values. This discrepancy has been coined the *proton radius puzzle* [3]. The proton and deuteron radius discrepancies could originate from a problem in the determination of the Rydberg constant [4] and indeed a recent measurement of the Rydberg constant by means of the 2S-4P transition in ordinary hydrogen performed in Garching [5] suggested a smaller Rydberg constant and hence a smaller proton radius also in hydrogen. However, the large proton radius has recently been confirmed by a measurement of the 1S-3S transition in Paris [6].

Recently, also ^{3}He and ^{4}He were measured by laser spectroscopy of the muonic ions. Using modern theory summarized in [2], we determine the charge radii of the these nuclei with 10 and 6 times higher accuracy than the values from elastic electron scattering.

In this contribution, we will present ongoing and planned measurements of the CREMA collaboration targeting the (magnetic) Zemach radius of the proton [7], by laser spectroscopy of the hyperfine structure in μp. We will also present plans to extend the Lamb shift measurements to lithium and beryllium nuclei. With the muon as a sensitive probe for the nuclear structure, these measurements have the potential to improve the corresponding charge radii by a factor of 10 and 5, respectively. Comparing these measurements with studies from elastic electron-proton scattering events provides a suitable tool to test nuclear theory.

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Hyperfine structure in heavy muonic atoms

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We consider bound states between an atomic nucleus and a muon, so called muonic atoms. Especially for high charge numbers, the surrounding atomic electrons do not influence the muon and the systemis essentially hydrogenlike. Just as in normal atoms, there is fine andhyperfine splitting, but the significance of the various contributionsdiffers dramatically. In particular, nuclear structure effects are muchbigger, and vacuumpolarization effects are very important. We calculate the level structure in heavy muonic atoms, taking several QED and nuclear structure effects into account in first-order perturbation theory and beyond. Thereby, precise values of the hyperfine structure of muonic atoms are obtained [1] and the dependence of transition energies in muonic atoms on nuclear parameters is investigated.

[1]: Phys. Rev. A **96**, 032510 (2017)

Towards Sympathetic Cooling of a Single (Anti)Proton in a Penning Trap for a High-Precision Measurement of the Particle's Magnetic Moment

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[b] *Ulmer Fundamental Symmetries Laboratory, RIKEN, Wako, Japan*
[c] *Institut für Physik, Johannes Gutenberg-Universität, Mainz, Germany*
[d] *Helmholtz-Institut Mainz, Mainz, Germany*
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Precise comparisons of the fundamental properties of protons and antiprotons, such as magnetic moments and charge-to-mass ratios, provide stringent tests of CPT invariance, and thus, matter-antimatter symmetry. Using advanced Penning-trap methods, we have recently determined the magnetic moments of the proton and the antiproton with a relative precision of 0.3 p.p.b. and 1.5 p.p.b., respectively [1, 2].

Both experiments rely on sub-thermal cooling of the particle's modified cyclotron mode using feedback-cooled tuned circuits. This time-consuming process is ultimately required to identify single spin quantum transitions with high detection fidelity, which is a major prerequisite to apply the multi-trap methods that are essential for p.p.b. measurements.

Methods of laser cooling achieved unprecedented quantum control of trapped ions. However, they are not directly applicable to our experiments because the proton and antiproton lack the electronic structure required for laser cooling.

In order to advance our techniques and to drastically reduce the measurement time, we are currently implementing methods to sympathetically cool protons and antiprotons by coupling them to laser-cooled beryllium ions, using a common endcap method [3].

To this end, our collaboration has developed a new apparatus featuring a common endcap double Penning trap. Based on our calculations we expect that this new apparatus will enable us to prepare single protons and antiprotons with energies close to the Doppler limit of laser cooling within tens of seconds, which will ultimately reduce our particle preparation times by a factor of at least 50 [4].

In this poster we present the experiment and the status of our ongoing efforts to deterministically prepare single protons and antiprotons at mK-temperatures.

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A New Silicon Drift Detector System for Kaonic Atom Measurements

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Kaonic atoms provide a unique way to study the strong interaction in bound systems [1],[2],[3],[4]. The proposed kaonic deuterium measurement at J-PARC [5], [6] and DAΦNE [7] will add important results to the already existing kaonic hydrogen analysis, adding in particular values for the determination of the antikaon-nucleon scattering lengths a_0 and a_1 by measuring the energy shift and width of the 1s state. Additionally, the planned kaonic helium experiment at J-PARC will give new insight in the possible isotope shift between He-3 and He-4 [8].

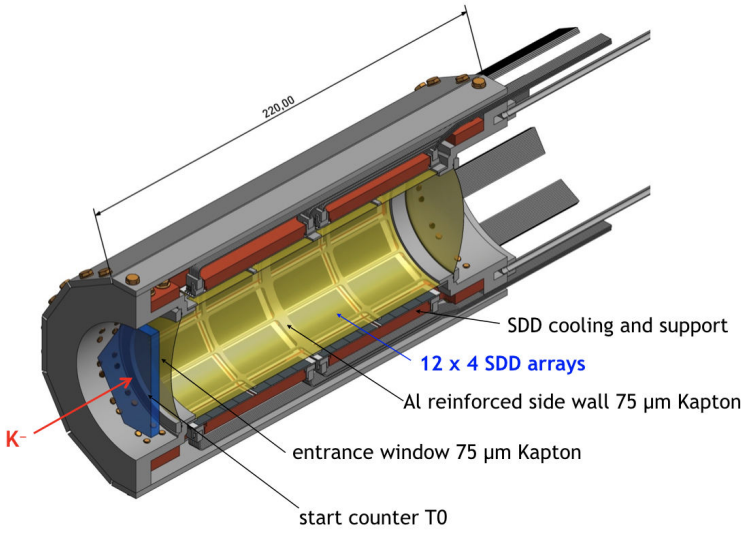

Figure 1: Sketch of the lightweight cryogenic target cell surrounded by 48 SDD arrays

For the kaonic deuterium measurement the 2p→1s shift will be measured by 48 SDD arrays surrounding a cryogenic target cell (see Figure 1). With newly developed amplifiers and specially designed Silicon Drift Detectors the shift and width of the 1s state can be measured with an accuracy better than 50 eV and 100eV, respectively. The SDDs have undergone several tests at the Stefan Meyer Institute concerning their energy resolution and stability. The latest tests have been performed to determine the timing resolution (drift time) of the SDD arrays, achieving a drift time below 500 ns at 150 K. Tests at lower temperature to reduce the drift time below 200 ns are planned in the near future.

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[3] M. Bazzi *et al.* (SIDDHARTA collaboration), Phys. Lett. **B 681** (2009) 310
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Charged particle veto detector for a kaonic deuterium measurement at DAΦNE

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Introduction

SIDDHARTA-2's aim is to perform a precise measurement of kaonic deuterium to determine X-ray transitions to the ground state (1s-level), such as to determine its shift and width induced by the presence of the strong interaction [1]. The analysis of the combined measurements of kaonic deuterium and kaonic hydrogen (already measured by SIDDHARTA [2]) will allow the extraction of the isospin-dependent antikaon-nucleon scattering lengths which are fundamental inputs of low-energy QCD effective theories.

Experimental Setup

Using the theoretical estimates for K^-d yields, which are one order of magnitude below the measured K^-p yields, an upgrade and optimisation of the SIDDHARTA apparatus is essential. An enhancement by at least one order of magnitude of the signal to background ratio is required for SIDDHARTA. Therefore, an active charged particle anticoincidence-veto-2 system is under construction, since each real X-ray signal from K^-d K_α transitions is accompanied by charged particles like protons and pions from final kaon absorption. We cannot veto all potential signals which are in coincidence with these particles, but we rather have to look at the positional correlation between SDDs and charged particle hits. Clearly, it is advantageous to detect the charged particle position as close as possible to the SDD cell to obtain a good signature of whether the events might origin from the SDDs or not.
The basic layout of the detector is shown in Fig.1. It is planned to use tiles made out of small organic scintillators with sizes of 50 x 12 x 5 mm^3, attached to one Silicon Photo-Multiplier (SiPM) with a sensitive area of 4 x 4 mm^2, which are shown in Fig.2. The main reasons for choosing organic scintillators are their fast response (short rise- and decay-times) and their high light yield. As detector SiPMs are chosen because SiPMs provide advantageous properties such as good timing, compactness and high photon detection efficiency (PDE).
We will present in detail the detector setup and discuss the first results of the test measurement.

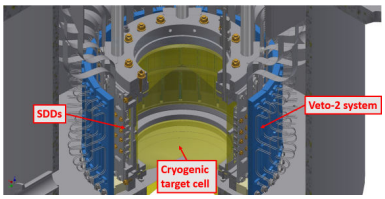

Figure 1: Setup of SIDDHARTA-2

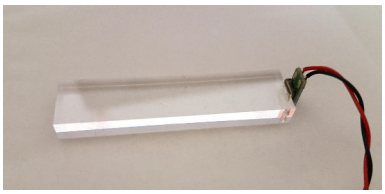

Figure 2: Scintillator tile with SiPM

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Status Update of NoMoS

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We present a new method of spectroscopy, utilizing a drift effect to disperse charged particles in a uniformly curved magnetic field [1]. The curved field results in a drift of the charged particles perpendicular to the radius of the curvature and to the magnetic field, which is proportional to the particle's momentum. A spatial-resolving detector will determine the momentum spectra. The first realization, called NoMoS (Neutron decay prOducts MOmentum Spectrometer) [2], will measure correlation coefficients in free neutron beta decay to test the Standard Model of particle physics and to search for physics beyond [3,4]. Currently, the focus is on the design and the construction of the magnet system.

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3D-imaging of antimatter annihilation using the ASACUSA Micromegas tracker

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The ASACUSA collaboration aims at measuring the ground state hyperfine splitting of antihydrogen for probing fundamental symmetries. A cryogenic double cusp trap for mixing antiprotons and positrons serves as an antihydrogen source for inflight spectroscopy [1, 2]. In order to be able to monitor the antihydrogen formation process, the ASACUSA Micromegas Tracking (AMT) detector was installed for detecting and reconstructing the antiproton and antihydrogen annihilations in the trap in three dimensions [3].

The AMT detector consists out of two curved gaseous detector layers using micromegas technology [4]. The layers form two half cylinders and are mounted concentrically with the trap electrodes on the upper side of the vacuum chamber containing the trap. A single, full-cylinder layer of plastic scintillator between the two Micromegas layers provides fast signals for triggering the read ou- of the micromegas channels. As an active gas, a mixture of argon (90%) and isobutane (10%) is used. The drift region has a height of 3 mm, while the amplification region has a height of 128 μm. A relatively high drift voltage of 1600 V and an amplification potential of 460 V are applied, which sufficiently reduce the influence of the Lorentz force on the drift electrons due to the magnetic field of the trap.

Besides explaining the AMT detector in detail and describing the event reconstruction algorithm, we present annihilation data recorded during the 2016 beam time. Annihilation data from antiprotons show that the AMT detector is able to discriminate between annihilations on-axis and on the inner electrode walls of the trap [5]. The latter type of events are the primary signal candidates to be antihydrogen atoms.

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Positron Production and Storage for Antihydrogen Production

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Antihydrogen is the simplest stable antiatom which can be produced at low energies. A sample of antihydrogen amenable to precision spectroscopic investigation would provide a stringent test of CPT symmetry and may provide a path to physics beyond the standard model.

The ASACUSA collaboration employs a cryogenic double cusp trap for mixing antiprotons and positrons, which serves as an antihydrogen source for inflight spectroscopy [1, 2]. Antiprotons are provided by the Antiproton Decelerator at CERN. Positrons from a radioactive ^{22}Na source with an activity of currently 0.51 GBq are slowed down to a few eV using a neon rare-gas solid moderator and accumulated in a Surko-type buffer gas trap. Typically, 6×10^6 positrons are accumulated within 30 s and transferred into the double cusp trap for mixing.

In this poster, the apparatus and methods used to produce, trap, accumulate, and condition positrons will be discussed. Planned new developments in positron temperature measurement and cooling will be shown, which will be important for improving the mixing efficiency. Calculations show that hydrogen production is optimal with a high density, low temperature positron plasma [3], encouraging recombination via three-body and radiative processes.

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Near threshold ionization of argon by positron impact

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Historically, positron impact ionization has been investigated using beams of positrons with extremely large energy spreads (ΔE~2eV). The development of trap-based positron beams has for the first time allowed routine measurements with thermal energy spreads [1]. In this work, the cross-section for positron impact ionization of argon has been studied with a high-resolution positron trap-based beam (ΔE~60meV). A new method has been developed to measure the electron yield from ionization allowing the very near threshold (Ei+2eV) region to be investigated [2].

In this region close to threshold, the ionization process should be well understood via the so-called Wannier threshold law. These first results show that the exponent of the power law deviates from those predicted by theory and is close to that for electron impact ionization [3]. At present, this observation is not understood, work continues with other targets to test the robustness of this finding.

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Low dimensional modeling of atomic and molecular systems

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In this contribution, we present our recent results on novel atomic 1D and 2D model potentials derived according to an unusual application of the Hohenberg-Kohn theorems [1]. We outline the construction of such low dimensional model potentials, which have the important property that their ground states densities equal the reduced exact ground state densities of the 3D hydrogen atom. We present some results of the analytical properties of the respective quantum system in 1D, and compare the resulting nontrivial atomic potential to the familiar low dimensional atomic Coulomb potentials [2].

Our motivation for these advanced model potentials is their potential use in simulations of atomic or simple molecular systems driven by strong fs laser pulses, since quantum features play a fundamental role in attosecond physics [3]. Currently, these experimental techniques enable to measure the electrons' dynamics in atoms and molecules with attosecond time resolution [4, 5]. However, this new quantum metrology demands more theoretical knowledge about the fundamental quantum properties of these processes.

We test the physical correctness of our low dimensional model potential based on our 3D simulation results of a hydrogen atom interacting with a strong, linearly polarized few-cycle laser pulse, computed with a numerical solution of the Schrödinger equation [6]: we compare its results to those of our DFT based and of other commonly used low dimensional atomic model potentials [2] using various quantities derived from the respective wave functions. Our results show that it is possible to achieve quantitatively acceptable results even in these situations by using our model system instead of the 3D simulations.

We also intend to present some advanced applications of this DFT based model potential: we construct a low dimensional hydrogen molecular ion and a 1D hydrogen molecule and investigate how our model potential can be used to construct low dimensional molecules. We also present how the electron clouds of these systems interact with the above mentioned few-cycle strong field laser pulse, which is linearly polarized parallel to the molecular axis.

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Towards a search for Dark Matter using atomic Dysprosium

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Studies of rotation curves of galaxies, initiated by Oort & Zwicky (1930's) and later by Rubin (1970's) led to the Dark Matter (DM) hypothesis and the subsequent evidence for the existence of Dark Matter and Dark Energy. Search for the elusive dark matter candidates has been going on since the early 1970's. Oddly, the Standard Model (SM) with all its tremendous successes (most notably, in the recent past, being the discovery of the Higgs boson at the LHC, CERN) has so far failed to provide an insight into the candidates that may directly or indirectly relate to Dark Matter or Dark Energy.

Experimental efforts (including the ones at the LHC, CERN) initiated towards the search of axions and WIMPs (Weakly Interacting Massive Particles), both of which are potential Dark Matter candidates, have still not produced any definitive outcome related to the origin of Dark Matter and the still yet elusive, Dark Matter particles. In our group, we are trying to search for possible Dark Matter (DM) candidates through precision atomic spectroscopy on dysprosium (Dy) atoms. Dysprosium (Dy) is an atomic system that has in the past been used for searching for possible variations of fundamental constants [1] with the aim of constraining possible dark matter candidates and also exploited for the search of parity-violating effects mediated by cosmic fields that may be part of dark matter. This experiment was also used towards a search for ultralight dilatonic dark matter [2] (that was also used to improve constraints on possible quadratic interactions of scalar dark matter by 15 orders of magnitude), and most recently, a search for possible exotic interactions sourced by massive bodies and mediated by light scalar bosons [3].

We are proposing to use the same system for performing precision ISS (Isotope Shifts Spectroscopy) measurements with sub-Hz precision, with the aim of searching for New Physics (NP) beyond the Standard Model (BSM) through possible non-linearities that may arise on a King Plot (KP) [4]. The idea is based on isotope shifts spectroscopy (ISS) and establishing a King Plot (KP) through frequency measurements across multiple isotopes of dysprosium (Dy) in the RF (Radio Frequency) and the optical domain. In an ideal scenario, the King Plot (KP) is linear with mass and frequency ratio scaling measured for two different transitions across multiple isotopes. Non-linearities in the King Plot may arise from possible dark matter candidates that couple to the atomic nucleus and electrons through short range forces. I shall present our experimental efforts that have been initiated towards this end with an emphasis on the current status and possible experimental outcomes.

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Nuclear-anapole-moment Effects in Diatomic Molecules

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In diatomic molecules, the rich and varied spectra and nearly degenerate energy levels provide huge enhancements for tiny physical effects, making it possible to look for new physics beyond the Standard Model in a single experiment. Nuclear-spin dependent parity-violating interactions and nuclear anapole moment effects in particular in diatomic molecules provide precise test of the electroweak theory of the Standard Model [1]. The nuclear anapole moment interaction coefficient W_A can be used to extract helpful information, which determines nuclear-spin dependent parity-violating interactions, from experiments [1]. It, specifically, depends on electronic structure and can be obtained from evaluating the matrix elements of the $\boldsymbol{\alpha}\rho(r)$ operator in the molecular spinor basis [1, 2, 3]. In this work, the W_A coefficients for the selected alkaline earth metal fluorides are reported with Relativistic Coupled Cluster theory combined with Finite Field approach and their properties are also discussed.

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Nonlinear Zeeman effect in boronlike highly charged ions

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The significant progress in the g-factor studies of highly charged ions was achieved in the last two decades, as a result of both experimental and theoretical work [1, 2]. The substantial accuracy improvement of the electron mass determination has been reached in these studies [3]. It's expected that high-precision g-factor measurements in hydrogen-, lithium- and boronlike ions will provide an independent determination of the fine structure constant α [4, 5]. The ARTEMIS experiment being carried out in GSI is an important step to this goal [6]. It aims at measurement of the Zeeman splitting in boron-like argon. It will be sensitive not only to the linear Zeeman effect (g factors) of the ground and first excited states, but also to the nonlinear effects in magnetic field. At present, the g factor has been well investigated theoretically including the QED, interelectronic-interaction and nuclear effects. The leading order of the quadratic Zeeman effect, the one-loop QED correction, and the one-photon-exchange correction for boronlike argon have been calculated in Ref. [7]. The leading order of the cubic Zeeman effect has been evaluated in Ref. [8]. We present *ab initio* QED calculation of the quadratic Zeeman effect for the ground and first excited states of boronlike ions in the wide range of Z including the first-order corrections: one-photon exchange, self-energy and vacuum polarization. Moreover, we evaluate the one-photon-exchange correction to the cubic Zeeman effect [9]. We employ both the perturbation theory in the magnetic interaction and the nonperturbative approach based on the numerical solution of the Dirac equation in the presence of external magnetic field. Both methods are fully relativistic, i.e., exact to all orders in αZ.

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The ALPHATRAP *g*-Factor Experiment

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[b] *Fakulty for Physics and Astronomy, University of Heidelberg, Germany*
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ALPHATRAP is a high-precision Penning-trap based experiment dedicated to the exploration of ground-state properties of heavy, highly charged ions (HCI). The major goal of ALPHATRAP is the measurement of the bound-electron gyromagnetic factor, or *g*-factor, which can be predicted to very high precision in the framework of bound-state quantum electrodynamics (BS-QED). The comparison of the experimental results with recent theoretical calculations will not only serve as a sensitive test of BS-QED, but also yields a new approach for the determination of fundamental constants such as the electron mass or the fine structure constant α.
The measurement of the bound-electron *g*-factor of a single HCI is performed in an improved cryogenic double Penning-trap setup, utilizing the continuous Stern-Gerlach effect. For injection of externally produced HCI up to $^{208}Pb^{81+}$ the ALPHATRAP experiment is coupled to various ion-sources, including the Heidelberg Electron-Beam Ion Trap. The ALPHATRAP apparatus including beamline, trap tower and electronics was successfully commissioned with single $^{12}C^{5+}$ and $^{40}Ar^{13+}$ ions, and is in preparation for its first *g*-factor measurement. This poster will give an overview of the experimental setup.

Searching for the first excited nuclear state of ^{229}Th

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The first excited nuclear state of ^{229}Th (Thorium) possesses the lowest excitation energy among the known nuclear levels. The excitation energy of this nuclear state is only 7.8±0.5 eV and can be excited directly using lasers. Which makes the design of a nuclear clock based on the first excited nuclear state of ^{229}Th becomes possible.

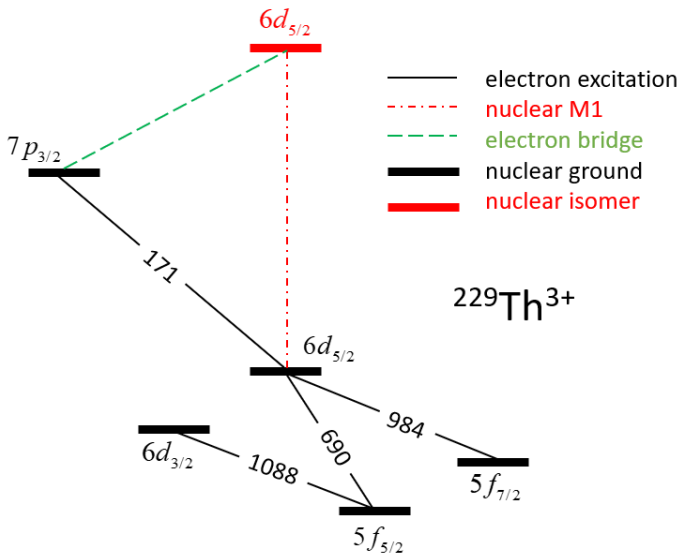

Figure 1: Electron excitation, nuclear M1 and electron bridge existed in ^{229}Th^{3+}

Kroger and Reich figure out the existence of this low energy nuclear level in 1976 [1]. In 2016, Lars von der Wense and colleagues observe the internal conversion electrons produced due to this nuclear level, which proves again the existence of this excited nuclear state [2].

We are proposed to measure the energy of this first excited nuclear state of ^{229}Th based on ^{229}Th^{3+} coulomb crystals in vacuum chamber. The procedure includes 1) Preparation of ^{229}Th^{3+}; 2) Confinement of ^{229}Th^{3+} using radio frequency quadrupole ion trap, together with Doppler laser cooling and high vacuum technology. Obtaining long lifetime and stabilized confined ^{229}Th^{3+} coulomb crystals; 3) Illuminating the ^{229}Th^{3+} Coulomb crystal with tunable lasers. Determing the energy range and lifetime of the first excited nuclear state of ^{229}Th.

The probability of first excited nuclear state of ^{229}Th (red in Figure 1) is small, makes it difficult to observe and measure directly. Alternate method is to measure the electron bridge (green in Figure 1) to obtain information of the first excited nuclear state of ^{229}Th indirectly.

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High-accuracy ab-initio calculations of magic wavelengths for the $2\,^3S_1 \rightarrow 2\,^1S_0$ transition of helium

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High-precision spectroscopy in helium has been achieved with sufficient accuracy to determine the fine-structure constant, to test QED theory, and to extract the nuclear charge radius. However, the determination of nuclear charge radius differences between ^{3}He and ^{4}He still disagree by 4σ from different frequency measurement of the $2\,^1S \rightarrow 2\,^3S$ and $2\,^3S \rightarrow 2\,^3P$ transitions [1, 2]. In order to measure the $2\,^1S \rightarrow 2\,^3S$ transition with sub-kHz precision, W. Vassen group in VU University designs a 319 nm magic wavelength trap to eliminate the ac Stark shift [3]. So far, there is lack of ab-initio calculation for the magic wavelengths of helium. In present work, a large-scale full-configuration-interaction calculation based on Dirac-Coulomb-Breit (DCB) Hamiltonian is performed for helium. Different from our previous RCI method [4], the mass shift operators are included directly into the DCB Hamiltonian. Furthermore, the non-relativistic calculations of helium are also carried out by using the Hylleraas-B-spline method. All the magic wavelengths from two different theoretical methods are consistent, and present RCI method predicted the magic wavelength 319.816 07(2) nm for ^{4}He, which provides theoretical support for experimental design of the magic wavelength optical trap.

No.	Hyllerass-B-splines	RCI	Ref. [3]
1	412.16(4)	412.167(1)	411.863
2	352.299(6)	352.336 7(1)	352.242
3	338.641 3(2)	338.683 5(1)	338.644
4	331.240 3(1)	331.284 63(2)	331.268
5	326.633 8(1)	326.678 87(2)	326.672
6	323.544 5(1)	323.589 79(2)	323.587
7	321.366 2(1)	321.411 36(2)	321.409
8	319.771 1(1)	319.816 07(2)	319.815
9	318.566 8(1)	318.611 62(5)	318.611

Table 1: The magic wavelengths (in nm) for the $2\,^1S_0 \rightarrow 2\,^3S_1(M_J = \pm 1)$ transition of ^{4}He.

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Hylleraas-B-spline basis set and its application of energies, polarizability and Bethe-logarithm of helium

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For solving the Hamiltonian eigenvalue problem of a two-electron atomic system, the Hylleraas-B-spline, H-B-spline, basis set is constructed through coupling the correlation term r_{12} and the traditional B-spline basis set [1]. This basis overcomes the ground state difficulty of using the traditional B-spline-type basis and inherits the property of fitting a wider range of initial states in one diagonalization. In the energy calculation for ground state of helium, the accuracy of our result using H-B-spline basis has 7 significant digits higher than using traditional B-spline basis. Combing the sum over pseudostates approach, we calculated the polarizability of helium. In two gauges, the results of polarizabilities for low-lying states of helium reached 8 significant digits at least. And the relative difference of the results of two gauges reached 10^{-11}. Recently, we extend this basis to the non-relativistic Bethe-logarithm, BL, calculations. Using H-B-spline basis, our preliminary results of BL arrived 7 significant digits for the $2\ ^3S - 10\ ^3S$ states of helium.

States	Hyllerass-B-splines	Ref. [2]	Ref. [3]
$2\ ^3S$	4.3640364*(1)*	4.36403682(1)	4.3640354
$3\ ^3S$	4.3686666*(1)*	4.36866692(2)	4.3686665
$4\ ^3S$	4.3697230*(2)*	4.36972344(5)	4.3697229
$5\ ^3S$	4.3700782(2)	4.37007831(8)	4.3700791
$6\ ^3S$	4.3702286*(4)*		4.3702300
$7\ ^3S$	4.370302(1)		4.3703043
$8\ ^3S$	4.3703442*(2)*		4.3703450
$9\ ^3S$	4.370367(1)		4.3703690
$10\ ^3S$	4.370382(1)		4.3703841

Table 1: Comparison of BL for the $n\ ^3S$, n up to 10, states of helium. Units are a.u.

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Recent progresses in building a femtosecond extreme-ultraviolet (XUV) comb at WIPM

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Optical frequency comb in the XUV region has attracted a great deal of attention since its first demonstration in 2005 [1-2]. On one hand, it provides laser in the XUV region with narrow band width for the first time. This advance pave the way for measuring important transitions in the XUV region. For example, the 1S-2S transition of He, He^+, and Li^+ at 120 nm, 61 nm, and 40.7 nm, respectively. On the other hand, ultrafast processes on the attosecond/femtosecond time scale are evolved during high order harmonics generation when the laser intensity inside an enhancement cavity reaches ~10^{13} W/cm^2. Thus, ultrafast science can be revealed with high harmonic spectrum, coherence measurements, etc., with the benefit of high repetition rate. In a word, XUV comb leads to another joint frontier of precision spectroscopy and ultrafast science [2].

In this work, we report on the recent progress in building an XUV comb at Wuhan Institute of Physics and Mathematics (WIPM). High harmonic generation in an enhancement cavity is adopted to realize the short wavelength in the XUV region. The driving IR comb has a repetition rate of 100 MHz, a pulse duration of ~100 fs and a maximum output power of 100 W. After mode matching, this IR comb is coupled into a 3-meter long travel wave enhancement cavity. The enhancement cavity is designed to have a buildup of ~200 and a beam diameter of ~20 μm at the focus. With the PDH method, we were able to lock the length of the enhancement cavity to the repetition rate of the driving laser. Up to now, we have achieved an average power of 3.6 kW in the enhancement cavity and intra-cavity high harmonic generation is on the way.

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

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The 1S-2S two-photon transition frequency in hydrogen can be measured most accurately compared to other transitions in hydrogen due to its narrow natural linewidth, and serves as a corner stone for fundamental constants [1]. However, only a combination of the precisely known 1S-2S transition with additional measurements allows to extract specific constants such as the proton root mean square charge radius r_{p} as well as the Rydberg constant R_∞, and to test the consistency of Quantum Electrodynamics. More precise measurements of the 2S-nP transition frequencies (e.g. with $n = 4,\ 6$) can be used to overcome current limitations in the framework of determining fundamental constants.

The value of r_{p} has become particularly interesting since the discovery of the apparent discrepancy with muonic hydrogen [2]. Important steps towards the solution of this so-called proton radius puzzle are more precise measurements of other transitions in hydrogen. Recently, the 2S-4P transition has been measured in our group with a relative uncertainty of 4 parts in 10^{12} [3]. Combining this result with the 1S-2S transition frequency leads to the r_p value which is 3.3 combined standard deviations smaller than the value deduced from previous hydrogen world data, but in good agreement with the value from muonic hydrogen. Since the origin of this discrepancy is currently unknown, more measurements with even higher precision are needed.

Using the same apparatus as for the 2S-4P data, we aim to measure the 2S-6P transition with an improved uncertainty. With a narrower natural linewidth of 3.8 MHz (as opposed to 12.9 MHz for 2S-4P), the 2S-6P transition has the potential to determine the line center more accurately. In addition to the known challenges from the previous experiment, the new transition requires to rebuild the system for 410 nm (2S-6P) as opposed to 486 nm (2S-4P) laser light. The shorter wavelength leads to difficulties such as a complete re-design of our collimator used for the active fiber-based retroreflector [4], and increased Rayleigh scattering in the optical fiber resulting in etalon-like effects. This poster reports on the current status of the 2S-6P hydrogen experiment, with a particular focus on the upgrade for shorter wavelength.

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First results of the VIP2 experiment

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The Pauli Exclusion Principle (PEP) is the foundation for our understanding of physics where systems of fermions are concerned. Therefore, it is important to make precision tests of the PEP. In a pioneering experiment, Ramberg and Snow supplied an electric current to a Cu target, and searched for PEP violating atomic transitions of "fresh" electrons from the current [1]. The non-existence of the anomalous X-rays from such transitions then set the upper limit for a PEP violation. The VIP (VIolation of Pauli Exclusion Principle) experiment could set this upper limit to 4.7×10^{-29} [2] with the described method. The follow-up project VIP2 improves experimental parameters with the goal to set an even lower limit. First results were presented in [3], which could already improve the limit provided by VIP. The VIP2 experiment and the newest results from a longer data taking period in the underground laboratory of Gran Sasso (LNGS) will be presented.

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A new approach for measuring antiproton annihilation at rest with Timepix3

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Ultra precise tests of CPT (charge, parity, time) symmetry, in view of the baryon asymmetry in the Universe is the main motivation for the experiments at the Antiproton Decelerator (AD) at CERN. Most of them focus on studying antihydrogen - the only stable, neutral antimatter system available for laboratory study. Crucial to the success of these experiments is the efficient detection and correct tagging of antiprotons and antihydrogen. Mostly it is achieved with tracking detectors, through the reconstruction and extrapolation of the trajectories of charged pions produced in the annihilation process [1,2,3,4]. These detectors determine the time and position of antiproton annihilations and usually consist of layers of silicon strip modules [1,2] or scintillating bars and fibres [3,5].

We present here a different detection method, using a pixel detector, where the antiprotons annihilate inside the detector volume or in a thin foil in front of it. This approach gives high resolution on the annihilation position (tens of μm), making it dominant for experiments with such requirement [6]. When integrated with a conventional tracking detector, the method makes possible to detect and identify most of the products in antiproton-nucleus annihilation (charged pions, protons, alphas and heavy fragments). A detailed study of their multiplicity and energy distributions is essential for tuning the physics models in the Monte Carlo simulations (e.g. GEANT4) in the low-energy region.

This work incorporates studies from two AD experiments, employing the Timepix3, an ASIC hybrid detector developed by CERN's Medipix3 collaboration, characterised with high spatial resolution and nanosecond precision on the Time-of-Arrival and Time-over-Threshold [7]. Direct detection of antiprotons was performed on a dedicated beam line within AEgIS [8], providing quantitative results on the tagging efficiency and the position resolution of the annihilation point, which will be discussed [9]. The measurement of the multiplicity and energy distributions of the prongs in antiproton annihilations in different materials was set up in ASACUSA, where the information from a quad array of Timepix3 and the existing hodoscope was combined [3]. The advantages of having two detectors and a first glimpse on the results will be presented.

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Ramsey set-up for (anti-)hydrogen hyperfine spectroscopy

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In the framework of the Standard Model, CPT symmetry demands the same fundamental properties for matter and antimatter. The precise measurement of the ground state hyperfine structure of antihydrogen and its comparison to that of hydrogen is a sensitive test of CPT invariance. A Ramsey type beam spectroscopy method [1] has the potential to improve this precision by a factor of 10 over the existing Rabi type setup [2] at CERN. The design phase for this new set-up is underway and the case studies considering the microwave cavities and surface coils, which shall be used for perturbations will be presented. The most optimal solution from these cases will govern the decision whether to adapt to a longitudinal or transverse static magnetic field design. Although the characterisation of the spectrometer line will be done using hydrogen, its scalability for the case of antihydrogen shall also be discussed.

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Spectral lines from C-like to Ca-like tungsten

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In recent years, just like X-rays from few-electron ions, extreme ultraviolet rays (EUV) from highly charged heavy ions have attracted attention in the temperature diagnostics of tokamak plasmas such as International Thermonuclear Experimental Reactor (ITER). Among all possible high Z impurities in ITER, tungsten is expected to be the most abundant [1].

In this work, we investigate the radiative decay of some select ions of W in the range W^{68+} to W^{54+} and report the structure of of the spectral lines from these ions. The calculations have been carried out using multi-configuration Dirac-Fock wavefunctions with the inclusion of magnetic interaction, retardation and quantum electrodynamics effects [2]. The radiative decay wavelengths and rates are compared with currently available theoretical and experimental data [3].

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Tune-out wavelength calculation for helium

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The tune-out wavelength is the wavelength at which the frequency dependent polarizability of an atom vanishes. It can be measured to very high precision by means of an interferometric comparison between two beams. This paper is part of a joint theoretical/ experimental project with K. Baldwin et al. (Australian National University) [1] and L.-Y. Tang et al. (Wuhan Institute of Physics and Mathematics) [2] to perform a high precision comparison between theory and experiment as a probe of atomic structure, including relativistic and quantum electrodynamic effects. We will report the results of calculations for the tune-out wavelength that is closest to the $1s2s\ ^3S - 1s3p\ ^3P$ transition of ^{4}He at 413 nm. Our result for the $M = 0$ magnetic substate, obtained with a fully correlated Hylleraas basis set, is $413.084\,109\,440(12)$ nm, where the figures in brackets indicate the computational uncertainty. This includes a leading relativistic contribution of $-0.059\,218\,5(16)$ nm from the Breit interaction as a perturbation, and a relativistic recoil contribution of $-0.000\,044\,47(17)$ nm. A leading QED correction of 0.004 150 93 nm is also included, but not higher-order corrections or their uncertainty. The results will be compared with recent relativistic CI calculations [2].

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Guiding and manipulating Rydberg positronium using inhomogeneous electric fields

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The short ground-state lifetime of Positronium (Ps) makes it challenging to perform precision-spectroscopy studies that require long interaction times. However, when excited to Rydberg states the annihilation rate of Ps becomes negligible [1], and the lifetime is dominated by fluorescence to low lying states. In addition, Rydberg Stark states with large Stark energy shifts have significant electric dipole moments which provide a mechanism by which forces can be applied to Ps atoms using inhomogeneous electric fields [2].

In a recent series of experiments we selectively excited individual Stark-states of Ps [3], guided the atoms using inhomogeneous electric fields in an atomic guide [4], and modified the guide to select a portion of the velocity distribution of the atoms with kinetic energies of ∼45 meV [5]. Having a beam of slow Rydberg Ps atoms will lead to a number of applications including trapping Ps, measuring the Rydberg constant in a purely leptonic system [6], scattering and merged beams experiments, and potential antimatter gravity measurements.

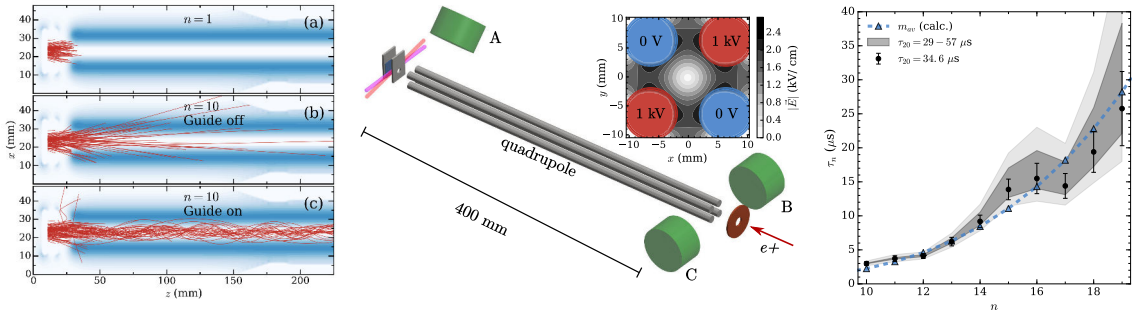

Figure 1: (Left) Trajectory simulation for Ps in the ground state (a), $n = 10$ (b) and guided $n = 10$ with inhomogeneous electric fields. (Center) Experimental setup and detector position. (Right) Measured and calculated fluorescence lifetimes of Rydberg states ranging $n = 10$ to 19.

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Testing fundamental interactions on light atoms

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We critically examine the current status of theoretical calculations of the energies and the isotope shift of the lowest-lying states of helium, searching for unresolved discrepancies with experiments. Calculations are performed within the nonrelativistic quantum electrodynamics expansion in powers of the fine structure constant α and the electron-to-nucleus mass ratio m/M. For energies, theoretical results are complete through orders $\alpha^6 m$ and $\alpha^6 m^2/M$, with the resulting accuracy ranging from 0.5 to 2 MHz for the $n = 2$ states. The isotope shift between ^{3}He and ^{4}He is treated theoretically with a sub-kHz accuracy, which allows for a high-precision determination of the differences of the nuclear charge radii δr^2. Several such determinations, however, yield results that are in a 4σ disagreement with each other. Apart from this, we find no significant discrepancies between theory and experiment for the helium atom.

Further, we present the complete relativistic $O(\alpha^2)$ nuclear structure correction to the energy levels of ordinary (electronic) and muonic hydrogen-like atoms. The elastic part of the nuclear structure correction is derived analytically. The analytical result is verified by high-precision numerical calculations. The inelastic $O(\alpha^2)$ nuclear structure correction is derived for the electronic and muonic deuterium atoms. The correction comes from a three-photon exchange between the nucleus and the bound lepton and has not been considered in the literature so far. In the case of deuterium, the inelastic three-photon exchange contribution is of a similar size and of the opposite sign as the corresponding elastic part and, moreover, cancels exactly the model dependence of the elastic part. The obtained results affect the determination of nuclear charge radii from the Lamb shift in ordinary and muonic atoms.

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Precision Physics of Simple Atomic Systems

Sunday	Session	Monday 14th of May — Speaker / Affiliation / Collaboration	Talk Time (min)	Session	Tuesday 15th of May — Speaker / Affiliation / Collaboration	Talk Time (min)	Session	Wednesday 16th of May — Speaker / Affiliation / Collaboration	Talk Time (min)	Session	Thursday 17th of May — Speaker / Affiliation / Collaboration	Talk Time (min)	Session	Friday 18th of May — Speaker / Affiliation / Collaboration	Talk Time (min)
9:00		WELCOME Karshenboim, Widmann	25	Tu1	Makoto Fujiwara *TRIUMF, Vancouver, CA / ALPHA*	25	We1	Michael Heiss *ETH, Zürich, CH*	25	Th1	Lakshmi Natarajan *Univ. Mumbai, IN*	25	Fr1	Shuiming Hu *Univ. Science & Technology, CN*	25
	Mo1 New SI	David Newell *Gaithersburg, US / NIST*	30	Antihydrogen & Antiprotonic He	Masaki Hori *MPQ, Garching, DE*	25	Positronium & Muonium	Gregory Adkins *F&M College, Lancaster, US*	25	QED, *g*-factors #3	Dmitry Glazov *St. Petersburg State Univ., RU*	25	Molecules #2	Piotr Wcisło *N. Copernicus Univ., Torun, PL*	25
		Arnold Nicolaus *Braunschweig, DE / PTB*	20		Filip Ficek *Jagiellonian Univ., Krakow, PL*	20		Toya Tanaka *Univ. Tokyo, JP*	25		Stefan Schmidt *Univ. Mainz, DE*	20		Cunfeng Cheng *Vrije Univ. Amsterdam, NL*	20
≈ 10:30		Lara Risegari *LCM-LNE Cnam, FR*	20		Stefan Ulmer *RIKEN, JP / BASE*	25		Anna Soter *PSI, Villigen, CH*	20		Andrzej Czarnecki *Univ. Alberta, Edmonton, CA*	20		Dmitrii Chubukov *St. Petersburg State Univ., RU*	20
COFFEE		10:35 to 11:05	30		10:35 to 11:00	25		10:35 to 11:05	30		10:30 to 11:00	30		10:30 to 11:00	30
≈ 11:00	Mo2	Xin Tong *WIPM, Wuhan, CN*	25	Tu2	Stephan Schiller *Univ. Düsseldorf, DE*	25	We2	Mariusz Puchalski *A. Mickiewicz Univ., Poznań, PL*	30	Th2	Catalina Oana Curceanu *INFN, Frascati, IT*	30	Fr2	Fabian Allmendinger *Univ. Heidelberg, DE*	20
	Special Transitions	Remi Geiger *LNE-SYRTE, Paris, FR*	20	Electron & Proton Masses	Fabian Heiße *MPI-K, Heidelberg, DE*	25	Molecules #1	Edcel Salumbides *Vrije Univ. Amsterdam, NL*	30	Exotic Atoms	Emiliano Mocchiutti *INFN, Trieste, IT*	25	Symmetry Violation & EDMs	Dionysios Antypas *Helmholtz Institute, Mainz, DE*	20
		James Calvert *LNE-SYRTE, Paris, FR*	20		Jean-Philippe Karr *Univ. d'Evry-Val d'Essonne, FR*	20		Stefania Gravina *Univ. Luigi Vanvitelli, Caserta, IT*	25		Sohtaro Kanda *RIKEN, JP*	25		Leonid Skripnikov *PNPI, Gatchina, RU*	20
≈ 12:30		Carl Carlson *College W&M, Williamsburg, US*	20		Vladimir Korobov *BLTP JINR, Dubna, RU*	20					Savely Karshenboim *MPQ, Garching, DE*	20		Bernhard Maaß *TU Darmstadt, DE*	20
LUNCH		12:30 to 14:00	90		12:30 to 14:00	90		12:30 to 14:15	105		12:40 to 14:00	80		12:20 to 13:40	80
≈ 14:00	Mo3	Claudio Lenz Cesar *Fed. Univ. Rio d. Janeiro, BR / ALPHA*	25	Tu3	Zoltan Harman *MPI-K, Heidelberg, DE*	25		Excursion Stift Klosterneuburg		Th3	Yu Sun *Univ. Science & Technology, CN*	25	Fr3	Hailong Ma *IHEP, Beijing, CH / BESIII*	30
	Antihydrogen	Bernadette Kolbinger *SMI, Vienna, AT / ASACUSA*	45	QED, *g*-factors #2	Martin Höcker *MPI-K, Heidelberg, DE*	20				Helium 3-body-system	Wim Vassen *Vrije Univ. Amsterdam, NL*	20	Hadrons	Johan Messchendorp *Univ. of Groningen, NE / BESIII*	
		Chloé Malbrunot *CERN, CH / ASACUSA*			Andreas Hannes Mooser *RIKEN, JP*	25		14:15 Meeting Point: Schwedenplatz (15min walk from Venue!)			Li-Yan Tang *WIPM, Wuhan, CN*	25		Sergei Gribanov *BINP, Novosibirsk, RU*	20
≈ 15:30		Valery Nesvizhevsky *ILL, Grenoble, FR*	25		Fabian Schmid *MPQ, Garching, DE*	20					Kelin Gao *WIPM, Wuhan, CN*	25		Ivan Logashenko *BINP, Novosibirsk, RU / CMD-3*	45
COFFEE		15:35 to 16:05	30		15:30 to 16:00	30					15:35 to 16:05	30		Alexey Kharlamov *BINP, Novosibirsk, RU*	
≈ 16:00	Mo4	Eite Tiesinga *Gaithersburg, US / NIST*	30	Tu4	Lothar Maisenbacher *MPQ, Garching, DE*	30		14:30 Bus Departure		Th4	Rene Sedmik *Atominstitut, TU Wien, AT*	25		Closing Remarks	
	QED, *g*-factors #1	Aleksei Malyshev *St. Petersburg State Univ., RU*	30	Hydrogen	Simon Thomas *Lab. Kastler-Brossel, Prais, FR*	25		15:15 to 17:15 Guided Tour Stift Klosterneuburg		Casimir & Cosmology	Hongwei Yu *Hunan Normal Univ., Hunan, CN*	20	LEGEND	Fundamental Constants & Transitions Antimatter Exotic Atoms QED, *g*-factors Electron, Muon, Few Electron Systems... Atoms & Molecules Proton-Radius Puzzle other Cosmology, Symmetry, Hadrons Poster Sessions & Social Prog. Coffee & Lunch Breaks	LEGEND
		Stefano Laporta *Univ. Padova, IT*	30		Arthur Matveev *MPQ, Garching, DE*	40					Carlos Vigo Hernandez *ETH, Zürich, CH*	25			
≈ 17:30					Alexey Grinin *MPQ, Garching, DE*						Yevgeny Stadnik *Univ. Mainz, DE*	20			
		Poster set-up	5		Poster set-up	5		Conference Dinner Stiftskeller 17:30 to 21:30 Bus departure (21:30) from underground parking			Manas Mukherjee *NUS, Singapore, SG*	15			
Welcome Reception 17h - 19h	Mo5 Posters	Poster Session #1 17:40 to ~19:00	80	Tu5 Posters	Poster Session #2 17:40 to ~19:00	80					Gordon Drake Poster Awards	10			

Alphabetic Participant List

Participant	Affiliation	Presentation(s)	Page
Gregory Adkins	Franklin & Marshall College	We1 (9:25-9:50)	36
Fabian Allmendinger	PI, Uni Heidelberg	Fr2 (11:00-11:20)	63
Alberto Alonso	UCL	Poster #18, Tuesday	103
Vitaly Andreev	MPQ, Garching	Poster #12, Tuesday	97
Dionysios Antypas	Helmholtz Institute, Mainz	Fr2 (11:20-11:40)	64
Tamara Babij	Australian National University	Poster #18, Monday	87
Lukas Berger	SMI, Vienna		
James Calvert	SYRTE	Mo2 (11:50-12:10)	10
Carl Carlson	College of William & Mary/JGU-Mainz	Mo2 (12:10-12:30)	11
Cunfeng Cheng	Vrije Universiteit Amsterdam	Fr1 (9:50-10:10)	61
Dmitrii Chubukov	St. Petersburg State University	Fr1 (10:10-10:30)	62
		Poster #1, Monday	72
Catalina Oana Curceanu	INFN / Laboratori Nazionali di Frascati (IT)	Th2 (11:00-11:30)	46
Andrzej Czarnecki	University of Alberta	Th1 (10:10-10:30)	45
Gordon Drake*	University of Windsor	Poster #17, Tuesday	102
Laura Dreissen	Vrije Universiteit Amsterdam	Poster #9, Monday	78
Michael Eides	University of Kentucky, USA		
Filip Ficek	Jagiellonian University	Tu1 (9:50-10:10)	21
Makoto Fujiwara	TRIUMF (CA)	Mo3 (14:00-14:25)	19
Kelin Gao	WIPM	Th3 (15:10-15:35)	53
Remi Geiger	Observatoire de Paris	Mo2 (11:30-11:50)	9
Dmitry Glazov	St. Petersburg State University	Th1 (9:25-9:50)	43
		Poster #6, Tuesday	91
Angela Gligorova	SMI, Vienna	Poster #14, Tuesday	99
Stefania Gravina	University of Campania "Luigi Vanvitelli"	We2 (12:05-12:30)	41
Sergei Gribanov	BINP, Novosibirsk	Fr3 (14:10-14:30)	69
Alexey Grinin	MPQ, Garching	Tu4 (17:15-17:35)	34
Mohammad Haidar	Kastler-Brossel Laboratory, Paris		
Yongliang Hao	RUG	Poster #5, Tuesday	90
Zoltan Harman	MPIK, Heidelberg	Tu3 (14:00-14:25)	27
Michael Heiss	ETH, Zurich	We1 (9:00-9:25)	35
Fabian Heiße	MPIK, Heidelberg	Tu2 (11:30-11:55)	24

*contribution in absence

Participant	Affiliation	Presentation(s)	Page
Christoph Heyl	Helmholtz-Institut Jena & DESY		
Martin Höcker	MPIK, Heidelberg	Tu3 (14:25-14:45)	28
Masaki Hori	MPQ, Garching	Tu1 (9:25-9:50)	20
Shuiming Hu	Univ Sci & Tech China	Fr1 (9:00-9:25)	59
Xia Hua	WIPM	Poster #8, Tuesday	93
Linqiang Hua	WIPM	Poster #11, Tuesday	96
Sohtaro Kanda	RIKEN (JP)	Th2 (11:55-12:20)	48
Jean-Philippe Karr	Kastler-Brossel Laboratory, Paris	Tu2 (11:55-12:15)	25
Savely Karshenboim	LMU, MPQ, Pulkovo	Th2 (12:20-12:40)	49
Alexey Kharlamov	BINP, Novosibirsk	Fr3 (14:50-15:15)	71
Bernadette Kolbinger	SMI, Vienna	Mo3 (14:25-14:45)	13
Jacek Komasa	Adam Mickiewicz University	Poster #2, Monday	73
Vladimir Korobov	Joint Institute for Nuclear Research	Tu2 (12:15-12:35)	26
Stefano Laporta	University of Padova	Mo4 (17:05-17:35)	18
Amélia Leite	SMI, Vienna		
Claudio Lenz Cesar	Federal University, Rio de Janeiro	Tu1 (9:00-9:25)	12
Alen Lika	SMI, Vienna		
XiaoJun Liu	WIPM		
Ivan Logashenko	BINP/NSU	Fr3 (14:30-14:50)	70
Hailong Ma	IHEP, CAS	Fr3 (13:40-13:55)	67
Bernhard Maaß	MPIK, Heidelberg / TU, Darmstadt	Fr2 (12:00-12:20)	66
Volkhard Mäckel	RIKEN (JP)	Poster #16, Monday	85
		Poster #17, Monday	86
Lothar Maisenbacher	MPQ, Garching	Tu4 (16:00-16:30)	31
Szilárd Majorosi	University of Szeged	Poster #2, Tuesday	88
Chloe Malbrunot	CERN	Mo3 (14:45-15:10)	14
Aleksei Malyshev	St. Petersburg State University	Mo4 (16:35-17:05)	17
Johann Marton	SMI, Vienna		
Arthur Matveev	MPQ, Garching	Tu4 (16:55-17:15)	33
Johan Messchendorp	KVI-CART	Fr3 (13:55-14:10)	68
Niklas Michel	MPIK, Heidelberg	Poster #11, Monday	80
Emiliano Mocchiutti	INFN, Trieste	Th2 (11:30-11:55)	47
Andreas Hannes Mooser	RIKEN (JP)	Tu3 (14:45-15:10)	29
Daniel Moser	TU, Wien	Poster #15, Monday	84
Manas Mukherjee	Centre for Quantum Technologies, NUS	Th4 (17:35-17:50)	58
Dan Murtagh	SMI, Vienna		
Amit Nanda	SMI, Vienna	Poster #15, Tuesday	100

Participant	Affiliation	Presentation(s)	Page
Lakshmi Natarajan	University of Mumbai	Th1 (9:00-9:25)	42
Anuradha Natarajan	S.I.W.S. College, Mumbai	Poster #16, Tuesday	101
Valery Nesvizhevsky	ILL	Mo3 (15:10-15:35)	15
David Newell	NIST	Mo1 (9:25-9:55)	5
Arnold Nicolaus	PTB	Mo1 (9:55-10:15)	6
Vitaly Ovsiannikov	Voronezh State University		
Krzysztof Pachucki	University of Warsaw		
Vojtech Patkos	Charles University in Prague	Poster #19, Tuesday	104
Duc Phan	SMI, Vienna		
Andreas Pichler	SMI, Vienna	Poster #13, Tuesday	98
Mariusz Puchalski	Adam Mickiewicz University	We2 (11:05-11:35)	39
Wolfgang Quint	Helmholtzzentrum GSI	Poster #6, Monday	75
Lara Risegari	LNE-Cnam	Mo1 (10:15-10:35)	7
Guy Ron	HUJI		
Edcel Salumbides	Vrije Universiteit Amsterdam	We2 (11:35-12:05)	40
Yang Sanjiang	WIPM	Poster #10, Tuesday	95
Stephan Schiller	Heinrich-Heine-Universität, Düsseldorf	Tu2 (11:05-11:30)	23
Fabian Schmid	MPQ, Garching	Tu3 (15:10-15:30)	30
Stefan Schmidt	Johannes Gutenberg University, Mainz	Th1 (9:50-10:10)	44
		Poster #10, Monday	79
Rene Sedmik	TU, Wien	Th4 (16:05-16:30)	54
Arijit Sharma	Johannes Gutenberg University, Mainz	Poster #4, Tuesday	89
Ting-Yun Shi	WIPM		
Martin Simon	SMI, Vienna		
Leonid Skripnikov	PNPI	Fr2 (11:40-12:00)	65
Anna Soter	PSI	We1 (10:15-10:35)	38
Yevgeny Stadnik	Johannes Gutenberg University, Mainz	Th4 (17:15-17:35)	57
Yu Sun	University of science and technology of china	Th3 (14:00-14:25)	50
Toya Tanaka	University of Tokyo	We1 (9:50-10:15)	37
Li-Yan Tang	WIPM	Th3 (14:45-15:10)	52
Simon Thomas	Kastler-Brossel Laboratory, Paris	Tu4 (16:30-16:55)	32
Eite Tiesinga	NIST	Mo4 (16:05-16:35)	16
Xin Tong	WIPM	Mo2 (11:05-11:30)	8
Carina Trippl	SMI, Vienna	Poster #13, Monday	82
Marlene Tüchler	Stefan Meyer Institute	Poster #14, Monday	83
Thomas Udem	MPQ, Garching		
Stefan Ulmer	RIKEN (JP)	Tu1 (10:10-10:35)	22
Roelant vanDierendonck	VUB		

Participant	Affiliation	Presentation(s)	Page
Wim Vassen	Vrije Universiteit Amsterdam	Th3 (14:25-14:45)	51
Carlos Vigo Hernandez	ETH, Zürich	Th4 (16:50-17:15)	56
Liming Wang	Henan Normal University, China	Poster #3, Monday	74
Piotr Wcislo	Nicolaus Copernicus University, Torun	Fr1 (9:25-9:50)	60
Günter Weber	Helmholtz Institute, Jena	Poster #8, Monday	77
Andreas Weigel	MPIK, Heidelberg	Poster #7, Tuesday	92
Eberhard Widmann	SMI, Vienna		
Albert Wienczek	University of Warsaw		
Markus Wiesinger	Max-Planck-Gesellschaft (DE)	Poster #12, Monday	81
Puxun Wu	Hunan Normal University		
Zong-Chao Yan	U. of New Brunswick and WIPM		
Hongwei Yu	Hunan Normal University	Th4 (16:30-16:50)	55
Yong-Hui Zhang	WIPM	Poster #9, Tuesday	94
Wan-Ping Zhou	Hubei University (CN)	Poster #7, Monday	76
Magdalena Zientkiewicz	University of Warsaw		
Johann Zmeskal	SMI, Vienna		