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

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

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

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

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

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

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

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

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

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* This work has been submitted to Phys. Rev. A.

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

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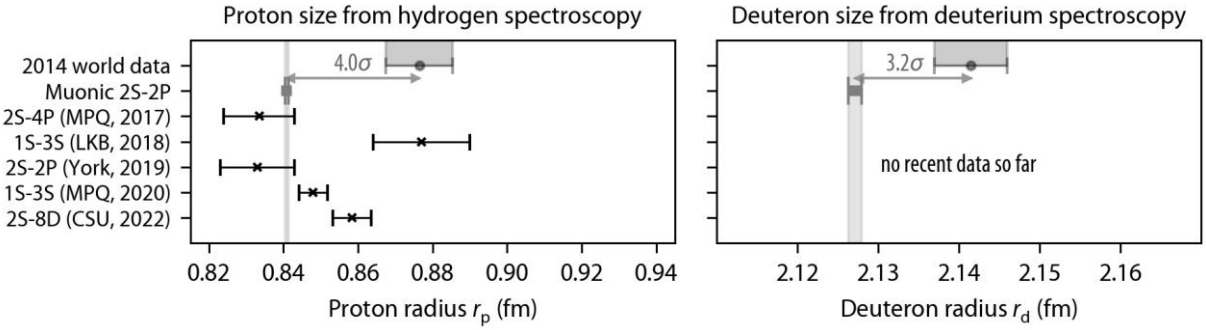
Both atomic hydrogen and deuterium can be used to determine physical constants and to test bound-state Quantum Electrodynamics (QED). By combining at least two transition frequency measurements in each isotope, the proton and deuteron radii, along with the Rydberg constant, can be determined independently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



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

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

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

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

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

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

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

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

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

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

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

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on behalf of the MuSEUM collaboration

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

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

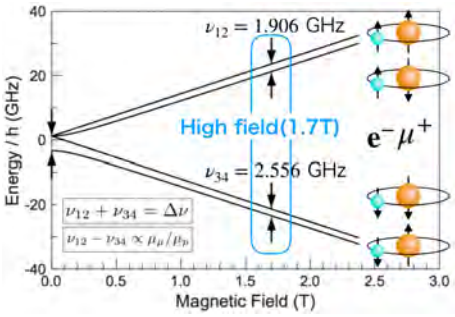

Figure 1: The energy levels of muonium under a magnetic field.

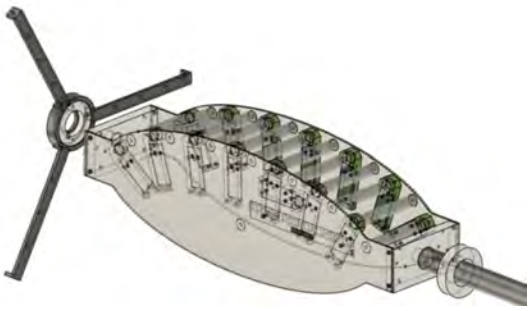

Figure 2: Magnetic field measurement system

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

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

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

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

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

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

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

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

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

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

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

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

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

First X-ray spectroscopy studies at the electron cooler of the low-energy storage ring CRYRING@ESR at GSI, Darmstadt have recently been performed for highly-charged ions [4, 5]. We report on the second campaign where MMC detectors have been used to study X-ray emission associated with the formation of excited helium-like uranium (U^{90+}) as a result of radiative recombination between stored U^{91+} ions and cooler electrons. The achieved spectral resolution of better than 90 eV at X-ray energies close to 100 keV enabled us to resolve the substructure of the Kα_1 and Kα_2 lines for the first time. This fivefold resolution improvement, compared to previous studies paves the way for future precision tests of strong-field QED and many-body effects.

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

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

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

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

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

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

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

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Hydrogen Optical Lattice Clock

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

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

Variational Dirac–Coulomb approach with explicitly correlated basis functions

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

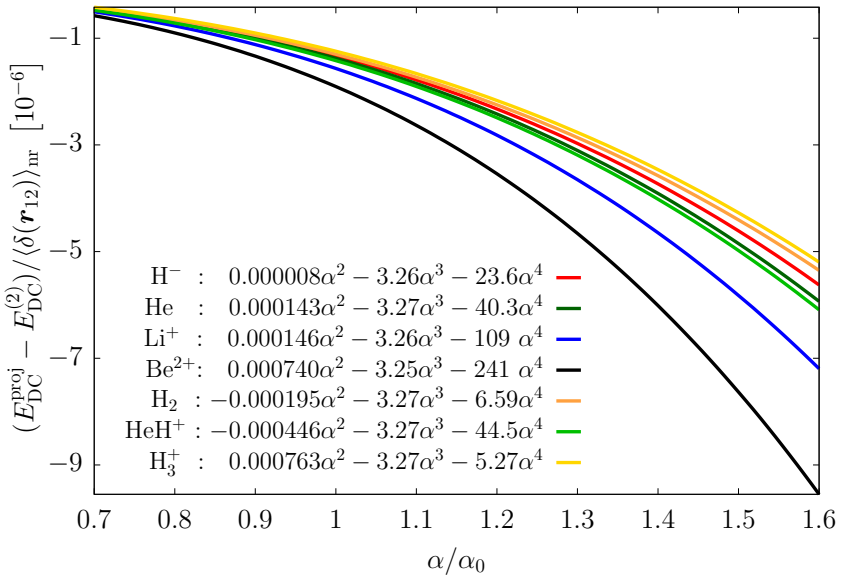

Figure 1: The dependence of the Dirac–Coulomb no-pair energy, ($E_\mathrm{DC}^\mathrm{proj}$) on the fine-structure constant (α). The non-relativistic energy and the α^2 perturbative energy correction ($E_\mathrm{DC}^{(2)}$) are extracted to highlight the agreement with the $\alpha^3 E_\mathrm{h}$ perturbative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

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

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

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

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The theoretical uncertainty of the bound-electron g-factor in heavy hydrogenlike ions is dominated by uncalculated QED Feynman diagrams with two self-energy loops. Precision calculations of these diagrams in which the interaction between electron and nucleus is treated exactly are needed to improve the theoretical accuracy of the bound-electron g-factor in the high-Z regime. Results of such calculations are highly relevant for ongoing and future experiments with high-Z ions as well as for an independent determination of fundamental constants such as the electron mass m_e and the fine structure constant α from the bound-electron g-factor [1]. Furthermore, comparisons of theory and experiment for heavy ions can serve as a probe for physics beyond the Standard Model after an improvement of the theoretical accuracy through the completion of two-loop calculations [2].
Due to the presence of ultraviolet divergences, two-loop self-energy Feynman diagrams need to be split into the loop-after-loop (LAL) contribution and the so-called F-, M- and P-terms which require different analytical and numerical techniques. The F-term corresponds to the ultraviolet divergent part of the nested and overlapping loop diagrams with free electron propagators inside the self-energy loops. The M-term corresponds to the ultraviolet finite part of nested and overlapping loop diagrams in which the Coulomb interaction in intermediate states is taken into account exactly. In our previous work, we have obtained full results for LAL and the F-term [3]. In this work, we present our results for the M-term contribution. P-term contributions correspond to diagrams which contain both bound-electron propagators inside the self-energy loops as well as an ultraviolet subdiagram and will be considered in a future work.

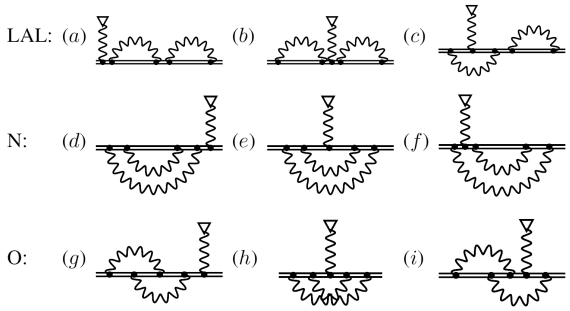

Figure 1: Furry-picture Feynman diagrams of the two-loop self-energy correction to the bound-electron g-factor.

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

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

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

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Testing Lorentz Symmetry using Deuterium

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

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

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Abstract ID : **71**

Ground state preparation for HD+ rovibration transition measurement

Content

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

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Presenter: ZHANG, QianYu (APM of CAS)

Contribution Type: Poster presentation

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

Precise determination of the $2s^22p^5$-$2s2p^6$ transition energy in fluorine-like Ni^{19+} utilizing a low-lying dielectronic resonance

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High precision spectroscopy of the low-lying dielectronic resonances in fluorine-like Ni^{19+} ions was studied by employing the electron-ion merged-beams method at the heavy-ion storage ring CSRm. The measured dielectronic-recombination (DR) resonances are identified by comparison with relativistic calculations utilizing the flexible atomic code (FAC). The lowest-energy resonance at about 86 meV is due to DR via $(2s^22p^6[^2S_{1/2}]6s)_{J=1}$ intermediate state. The position of this resonance could be determined within an experimental uncertainty of as low as ±4 meV. The binding energy of the 6*s* Rydberg electron in the resonance state was calculated using two different approaches, the Multi-Configurational Dirac-Hartree-Fock (MCDHF) method and the Stabilization Method (SM). The sum of the experimental $(2s^22p^6[^2S_{1/2}]6s)_{J=1}$ resonance energy and the theoretical 6*s* binding energies from the MCDHF and SM calculations, yields the following values for the $2s^22p^5\ ^2P_{3/2} \rightarrow 2s2p^6\ ^2S_{1/2}$ transition energy $149.056(4)_{exp}(20)_{MCDHF}$ and $149.032(4)_{exp}(6)_{SM}$, respectively. The theoretical calculations reveal that second-order QED and third-order correlation effects contribute together about 0.1 eV to the total transition energy. The present precision DR spectroscopic measurement builds a bridge which enables comparisons between different theories.

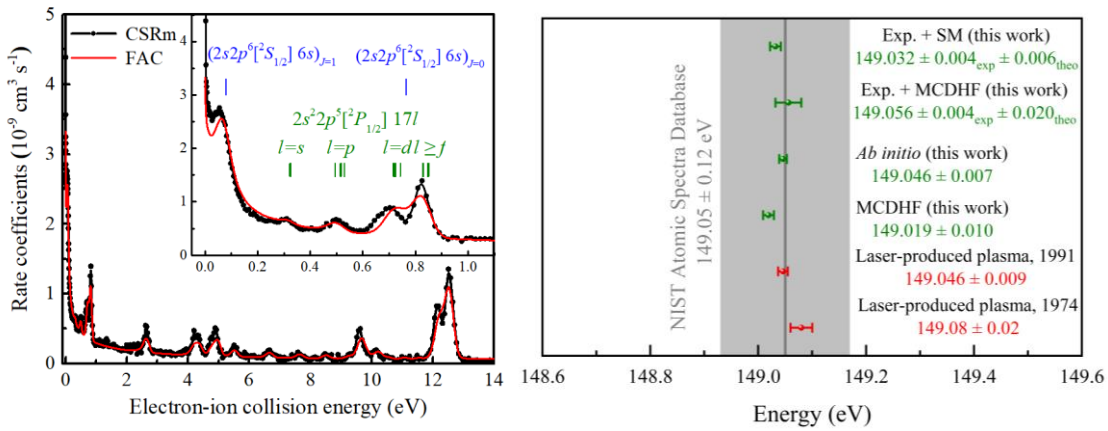

Figure 1. (Left) Experimental electron-ion recombination spectrum (black symbols) in comparison with the result of theoretical calculations utilizing the FAC code (red solid curve). The inset enlarges the low-energy resonances with their calculated resonances indicated by the vertical bars. (Right) A comparison of the present experimentally-derived and theoretically calculated $2s^22p^5\ ^2P_{3/2}$ -$2s2p^6\ ^2S_{1/2}$ transition energies with previous plasma observations and the NIST recommended data.

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Development of Electrodes for the Muon Penning Trap Experiment

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

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

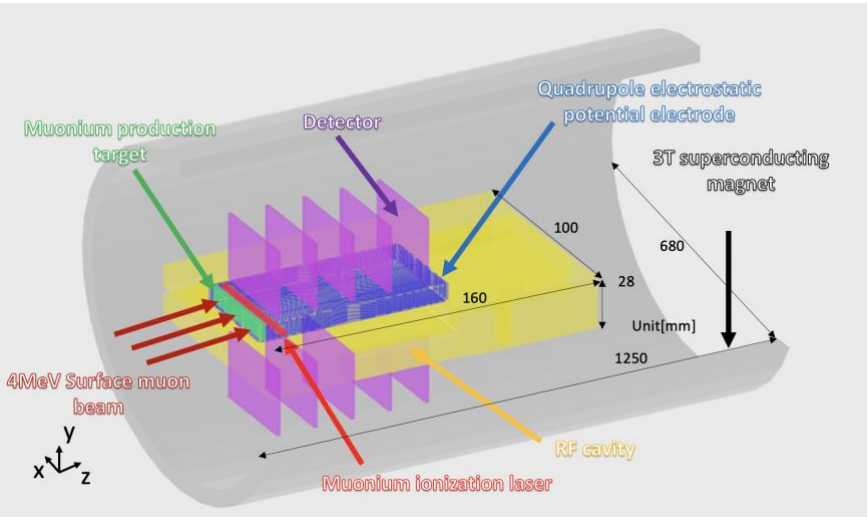

Figure 1: Schematic view of the Penning trap experiment of muons.