

# PLATAN 2019, Mainz – International Conference Merger of the Poznan Meeting on Lasers and Trapping Devices in Atomic Nuclei Research and the International Conference on Laser Probing

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Helmholtz Institute Mainz

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- Structural properties of elementary particles, nuclear systems using laser isotope techniques
- Laser ion sources for hot cavities, gas cells and jets
- Precision laser spectroscopy
- High precision mass spectrometry
- Spectroscopic routes to heavy and super-heavy elements
- Production and spectroscopy of exotic atoms
- Hyperfine/hypernuclear fingerprints
- Cooling and trapping techniques devoted to exotic ion beams
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- Applications

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# **Book of Abstracts**

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## A Cryogenic Stopping Cell used as an Ion Trap: Measuring Half-Lives and Decay Branching Ratios of Exotic Nuclei with the FRS Ion Catcher

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A novel method for the simultaneous and direct measurements of masses of exotic nuclei, half-lives, decay branching ratios and isomer excitation energies has been demonstrated with the FRS Ion Catcher at GSI. The measurement relies on the combination of a clean separation of the fragments in the FRS, a cryogenic stopping cell (CSC) with very high areal density (up to 10 mg/cm<sup>2</sup>), and a Multiple-Reflection Time-Of-Flight Mass Spectrometer (MR-TOF-MS) for high-precision broadband mass measurements.

The precursor ions are produced in the FRS, and stored for controllable durations in the CSC, which are long enough for them to decay via single or multiple channels. In this measurement, the CSC has been used as an ion trap for the precursors as well as for the recoils for the first time. Precursor and recoils are further extracted to the MR-TOF-MS, where they are identified and counted.

The feasibility of the method was demonstrated by measuring the alpha decay of <sup>216</sup>Po and the isomer-to-ground transition of <sup>119m2</sup>Sb. For <sup>119</sup>Sb, this is the first direct mass measurements of the ground and second isomeric states.

In the future, the method will be used to measure beta-delayed neutron emission probabilities.

## Development of the HITRAP cooling trap and EBIT experiments

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The last linear deceleration stage of HITRAP, the radio-frequency quadrupole, was successfully commissioned in 2014. After leaving the RFQ the ions need to be stored and cooled in the HITRAP cooling trap. However, several tests in the past years have shown the need for a new design of the trap with improved stability and voltage rigidity [1]. With the goal of reducing the number of electrodes and electrical connections as well as improving differential pumping of the trap vacuum, seven new trap electrodes were machined, gold plated and installed. Novel materials, such as BIN77 ceramics, were used in the process. We will present the new concept as well as the first results from tests with ions from the local electron beam ion trap (EBIT).

The SPARC-EBIT has been successfully in operation as a test ion source for HITRAP for already 10 years [2]. It can routinely deliver up to  $10^6$  HCl produced either from inert gasses or from externally injected singly charged ions [2]. The gas-based procedure is much simpler and delivers higher yields. To extend the gas based procedure to metallic ions we investigated the so-called MIVOC (Metal Ions from Volatile Compounds) method [3], which takes advantage of large vapor pressure of organic compounds with weakly bound metal atoms. With an electron beam energy of about 5 keV and small amounts of these compounds in the ionization chamber it was possible to produce  $\text{Fe}^{21+}$ ,  $\text{Sb}^{35+}$  and  $\text{B}^{5+}$ . We present the method and the results which significantly increase the number of elements and charge states possible to produce and deliver to experiments at the HITRAP facility.

Especially the production of boron ions offers an opportunity to characterize their penetration capacity of ultrathin carbon foils ( $\sim 5\text{nm}$ ), as a preparation for an online study of short-lived boron isotopes. Such foils will be implemented as a pumping barrier and molecule stripper in a low-energy gas catcher at Argonne National Laboratory in Chicago. This gas catcher is built for operation with radioactive, short-lived boron-8 beam, while the SPARC-EBIT provides a stable boron beam with sufficient rate to perform offline tests. The results of this investigation will also be presented.

This work was supported by BMBF under contract number 05P19RDFAA.

- [1] Z. Andelkovic, et. al.: GSI Scientific Report (2017)
- [2] G. Vorobjev, et. al., Rev. Sci. Inst. 83, 053302 (2012)
- [3] T. Werner, et. al., Rev. Sci. Inst. 71, 2038 (2000)

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## Using LARIMS on the Moon to Resolve Billion Year Uncertainties in Solar System History

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We have developed a portable laser ablation resonance ionization mass spectroscopy instrument for making Rb-Sr and Pb-Pb dating measurements, as well as producing elemental maps and organic measurements for context. This instrument, called the Chemistry, Organics, and Dating EXperiment (CODEX), can be used to constrain billion year uncertainties in the history of the inner solar system by producing new geochronology measurements on the Moon or Mars.

The history of the inner solar system is defined by relating lunar crater density to radiometric age of Apollo and Luna samples using models of impactor flux. These models are then extrapolated to cratered surfaces throughout the inner solar system to estimate surface age. However, returned samples primarily constrain the period from  $\sim 3.5$  to 4 Ga; as a result, the period from 2.5–3.5 Ga may have up to  $\pm 1$  Ga of uncertainties, depending on which cratering flux model is used. The lunar models, and hence the uncertainties between crater density and surface age, are extrapolated to surfaces of planetary bodies throughout the inner solar system. Consequences of this uncertainty

include the potential for the duration of peak lunar volcanism to extend for much longer than previously thought, requiring new geochemical models of lunar mantle evolution, and revision of our understanding of the development of one-plate planets. Furthermore, for Mars, the era of peak volcanism, volatiles, aqueous mineralogy, fluvial geomorphology, and most importantly habitability, could potentially be one billion years longer than previously recognized.

Using lunar analogs and meteorites such as LAP 02205 and MIL 05035, we show Rb-Sr and Pb-Pb dates from our Chemistry and Dating EXperiment (CDEX) instrument can produce in-situ radiometric dates to  $\pm 50$ -180 Ma ( $2\sigma$ ). CDEX is rapidly approaching flight readiness, with custom lasers that are undergoing environmental testing and a miniature flight mass spectrometer.

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## Improving the laser ablation ion source at SHIPTRAP

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In several areas of physics high-precision measurements of masses and mass differences,  $Q$ -values, are required. One such area is neutrino physics. For example, at SHIPTRAP the  $Q$ -values of the electron capture EC decay of  $^{163}\text{Ho}$  has been determined accurately [1].

To this end, the Penning-trap mass spectrometer SHIPTRAP coupled to a laser ablation ion source allows mass measurements with the required precision. To enable measurements on long-lived rare isotopes, the laser ablation, as well as transport and injection of the ions into the Penning traps have to be efficient. Therefore, with the aim to thermalize the laser-ablated ions and collect them in a narrow bunch, the ions are confined in a gas-filled miniature Radio-Frequency Quadrupole (mini-RFQ) [2], recently implemented at SHIPTRAP.

In order to further improve the laser ablation ion source and make it suitable for the production of radioactive ions from a target solution, additional design optimization and simulation studies are ongoing. In the case of  $^{163}\text{Ho}$  the full measurement was performed on a sample containing about  $10^{15}$  atoms. The current effort aims at the improving efficient preparation of short ion bunches from a target sample containing fewer atoms of radioactive material, which will extend the reach to more exotic species in the future. In this contribution an overview of the present status and planned upgrades of the laser ion source will be presented.

[1] S. Eliseev et al., Phys. Rev. Lett. **115**, 062501, (2015).

[2] F. Schneider et al., Eur. Phys. J. A **51**, 89, (2015).

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## Ion guide simulation for GALS setup

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The new setup called GALS (GAs cell based Laser ionization and Separation setup) is being created in Flerov Laboratory of Nuclear Reactions, JINR. This setup aims to synthesize and study new heavy neutron rich nuclei in the region of neutron closed shell  $N = 126$ . One of the important parts of the GALS is a radio-frequency ion guide, which captures laser-ionized isotopes of interest going out from the gas cell into vacuum through the supersonic nozzle along with the buffer gas. The ion guide carries the ions through differential pumping volumes towards acceleration electrode, after which they are mass-separated by analyzing magnet and go to detector system.

Several possible options were proposed for the ion guide system, e.g. sextupole or quadrupole segmented ion guide etc. To choose the most suitable system design, simulations of different ion guide options were carried out using the SIMION software package. Some additional code describing the gas jet was used in addition to the hard sphere collision model for correct ion trajectories simulations, especially in the very beginning of the ion guide. Estimations of possible particle losses and their time of flight on the way through the system were made. Energy spread and angle dispersion of the resulting ion beam, which are important for magnet analyzing and focusing system, were estimated as well. The final design of ion guide system will be presented.

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## The ground-state properties of 44-49Sc isotopes measured by collinear laser spectroscopy

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The ground-state properties of 44-49Sc isotopes measured by collinear laser spectroscopy

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Exotic nuclei in the calcium region have attracted wide attention in both experimental and theoretical studies [1,2]. Following earlier studies of neutron-rich K and Ca [3], the neutron-rich scandium isotopes around  $N=28$ , with one proton added to calcium atomic nuclei, were measured with high-resolution laser spectroscopy (COLLAPS) at CERN-ISOLDE [4]. The metastable state  $3d_{5/2} 3D_1$  in the Sc ion was populated via the resonance ionization laser ion source (RILIS), and the ionic transition of  $3D_1 \rightarrow 3F_2$  (364.3nm) was used for the collinear laser spectroscopy measurement. The observation of the hyperfine spectra of 44-49Sc allows the extraction of ground state properties, such as nuclear spins, moments and charge radii. Combining these results with earlier studies of potassium and calcium, will allow us to systematically investigate the shell structure information in this region, and to test advanced nuclear theory models based on chiral effective field theory.

In this talk, the details of experiment will be presented. The results related to the nuclear spins, moments and charge radii of 44-49Sc will be discussed by comparison with theoretical calculations.

[1] D. Steppenbeck et al., Nature 502, 207 (2013); F. Wienholtz et al., Nature 498, 346 (2013)

[2] Jason D Holt et al., J. Phys. G: Nucl. Part. Phys. 39 085111 (2012); G. Hagen et al., Phys. Rev. Lett 109, 032502 (2012)

[3] R. F. Garcia Ruiz et al., Phys. Rev. C, 91, 0421304 (2015); R. F. Garcia Ruiz et al., Nature Physics 12, 594 (2016); J. Papuga et al., Phys. Rev. Lett, 110, 172503 (2013); J. Papuga et al., Phys. Rev. C, 90, 034321 (2014)

[4] X.F. Yang et al., CERN-INTC-2017-087 / INTC-P-528 (2017)

## Direct Tests of Mass Models in the Heavy-Elements Region With Multiple-Reflection Time-of-Flight Mass Spectrometry

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Masses of exotic nuclei give access to the nuclear binding energy und thus help understanding nuclear structure and nucleosynthesis.

Challenges in measuring these masses include short half-lives and low production rates (down to a few counts per hour).

At the Fragment Separator FRS at GSI, exotic nuclei were produced by projectile fragmentation and fission of <sup>238</sup>U and <sup>124</sup>Xe primary beams.

Masses of the fragments were measured with the multiple-reflection time-of-flight mass spectrometer of the FRS Ion Catcher[1,2] with resolving powers up to and beyond 400,000.

To handle mass spectra with only partially resolved peaks and with only a few counts per ion species, an advanced data analysis method has been developed.

Precise determination of the peak shape and a reliable procedure of calibration, fit and error estimation lead to an increase of effective mass resolving power for overlapping peaks by a factor of up to three.

Isomers with excitation energies down to 334keV for <sup>133m</sup>Te and 279keV for <sup>134m</sup>Sb could be resolved.

Ground-state masses of 31 short-lived nuclides have been measured with mass uncertainties down to  $6 \cdot 10^{-8}$ .

Among them are <sup>213</sup>Rn with a half-life of 19.5ms and <sup>220</sup>Ra with a half-life of 17.9ms.

For seven nuclides this constitutes the first direct mass measurement.

These measurements now confirm that theoretical mass models in the region above <sup>208</sup>Pb are not yet accurate.

[1] W.R. Plaß et al., NIM B **317**, 457 (2013).

[2] T. Dickel, et al., PLB **744**, 137 (2015).

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## muCool: A novel low-energy muon beam for future precision experiments

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Experiments with muons and muonium atoms ( $\mu^+e^-$ ) offer several promising possibilities for testing fundamental symmetries of particle physics with high precision. Examples of such tests include the search for the muon electric dipole moment, measurement of the muon g-2 and muonium laser spectroscopy. These experiments could benefit from

a high-quality muon beam at low energy with small transverse size and high intensity. At the Paul Scherrer Institute we are developing a novel device that produces such a high-quality muon beam, reducing the phase space of a standard  $\mu^+$  beam by a factor of  $10^{10}$  with  $10^{-3}$  efficiency. The phase space compression is achieved by stopping a standard  $\mu^+$  beam in a cryogenic helium gas and subsequently manipulating the stopped  $\mu^+$  into a small spot using complex electric and magnetic fields in combination with gas density gradients. Finally, muons are extracted through a small orifice into the vacuum and into a field-free region. Various aspects of this compression scheme have been demonstrated in the last few years. Comparison of the measurements with GEANT4 simulations confirms that the proposed efficiency can be achieved. In this talk the current status will be reported.

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## The MORA project: optimization of the transparent ion trap geometry

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In the frame of MORA (Matter's Origin from the RadioActivity of trapped and oriented ions) project, an open transparent Paul trap is designed for the determination of the tripple correlation parameter "D" of laser polarized ions. The three-dimensional trap is composed of three conic rings pairs with a mid-plane symmetry. Trap design was inspired from the LPCTrap geometry [1], operated at GANIL from 2005 to 2013. The trap will be installed in a larger chamber and surrounded by four pairs of ion- and beta-detectors. A laser beam is used to polarize the trapped ions cloud. In order to improve the trapping time and broaden the detection solid angles, an optimization of the trap/electrodes geometry was carried out by minimizing high order harmonics and maximizing the quadrupolar term in the spherical harmonics expansion of the trapping potential. Our simulation is based on solving Laplace's equation with the AXIELECTROBEAM software developed at LPC Caen coupled to some  $\chi^2$  minimization.

[1] P. Delahaye et al., arXiv:1810.09246 [physics.ins-det], submitted to EPJA.

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## Quantum Mass Spectrometry: Using Optical Photons to Quantify Heavy Masses

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A new technique is in the final stage of development at the University of Granada to demonstrate for the first time single-ion Penning-trap mass spectrometry based on optical detection. A single laser-cooled  $^{40}\text{Ca}^+$  ion will be the detector, providing photons to quantify the energy gained of any accompanying trapped ion when the latter is probed with an external radiofrequency field in resonance with one of the two-ion-crystal's Eigenmotions. The magnetic field of the trap is the largest ever-used in laser-cooling experiments, which together with the level structure of the calcium ion, complicates its cooling significantly. Very recently we demonstrated cooling on an ion cloud, and the experiment is on track to reach in the short-term future the single laser-cooled  $^{40}\text{Ca}^+$  ion or any of the most naturally abundant even isotopes  $^{42,44,48}\text{Ca}^+$ . Furthermore, the simultaneous storage of two isotopic ions will allow demonstrating this proof of concept. In this contribution we will describe the TRAPSENSOR facility, the expected performance of the single-ion as sensor in the 7-tesla magnetic field, compared with the results obtained with a radiofrequency ion trap and will present the latest results obtained for an ion cloud. A second approach of the experiment separating physically the sensor and the accompanying ion as well as the applicability to superheavy elements will be underlined.

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## Towards Sympathetic Cooling of Protons and Antiprotons

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High precision measurements on trapped protons and antiprotons provide some of the most stringent tests of CPT symmetry in the baryon sector [1-3]. In particular, these experiments confirm CPT symmetry and provide further evidence of Lorentz invariance at the level of  $10^{-24}$  GeV on an absolute energy scale [4]. Further precision, however, is limited by high particle energies and requires



moving beyond the traditional techniques available in high precision cryogenic Penning trap experiments. We present a novel technique to sympathetically cool protons and antiprotons stored in separate traps, by coupling single particles to laser cooled ions via image currents induced in a common endcap electrode [5]. We place our work in the context of an improved  $g$ -factor measurement of the proton and show early results including the application of methods to measure sub-thermal single particle energy distributions in the laser cooled limit.

[1] C. Smorra, et al. Nature 550, 371 (2017).

[2] S. Ulmer, et al., Nature 524, 196 (2015).

[3] G. Schneider, et al., Science 358, 6366 (2017).

[4] Y. Ding, et al., PRL 94, 560088 (2016)

[5] M. Bohman, et al., J. Mod. Optics 65, 568 (2018).

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## Compact Collinear Laser Spectroscopy Apparatus for Ion Source Development and Students Training

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Collinear laser spectroscopy (CLS) is widely used to perform highly precise measurements of atomic spectra to extract nuclear properties, namely charge radii, magnetic dipole and electric quadrupole moments [Neugart et al. J. Phys. G. 44 064002 (2017)]. It has also been used to test QED calculations with light as well as highly charged heavy ions, and was applied on relativistic beams to test special relativity. We are developing a compact setup for CLS to be used as hands-on experience in the Students Lab to familiarize them with the technique and its science applications. Moreover, the apparatus will serve for quick equipment tests and ion source specifications. A first application in this respect will be the specification of a new laser ablation ion source that is foreseen to provide a broad range of stable elements with very low longitudinal and transverse emittance. A specially designed 90° bender with static electric fields is used to superimpose the ion beam with a collinear laser beam. A Faraday cup provides means to optimize the ion beam path and an optical detection region consisting of elliptic mirrors and photomultipliers are used for fluorescence detection. We will present details of the layout and the current status of the project together with some first measurements.

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## High accuracy theoretical investigations of heavy atoms and highly charged ions.

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Theory can provide important support at all the stages of spectroscopic experiments, from planning the measurements, through extracting the properties of interest from the data, and to the interpretation of the results and their comparison to theoretically predicted values. To this end, highly accurate calculations of atomic properties are needed. In order to be reliable, such calculations must include both relativistic effects and electron correlation on the highest possible level.

Relativistic coupled cluster is considered one of the most powerful methods for accurate calculations of properties of heavy elements. Two variants of this method are available. The single reference coupled cluster approach (SRCCSD(T)) is suitable for calculations of ground state properties in systems that can be well described by a single determinant. This approach can be used to obtain, for example, ionization potentials and electron affinities. The multireference Fock space coupled cluster method (FSCC) is particularly suited for calculations of excitation spectra. Both methods provide reliable high accuracy results and have strong predictive power. Depending on the properties and systems of interest, one can select the suitable method for the task, or use both approaches in a complementary manner.

A brief introduction to the two variants of the relativistic coupled cluster method will be provided and a new development that allows calculations of magnetic hyperfine structure constants will be presented. I will present a number of recent successful applications of the coupled cluster approach to properties of heavy atoms and highly charged ions, focusing on spectra and hyperfine structure parameters.

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## Resonance ionization for spatially resolved actinide secondary neutral mass spectrometry

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A variety of radionuclides has been released into the environment by nuclear weapons explosions, reprocessing of spent nuclear fuel and accidents in nuclear facilities. A potential future source of various nuclides is spent nuclear fuel, which has to be stored many thousands of years until the most radiotoxic nuclides have decayed significantly. The most accepted concept of waste management is deep geological waste disposal to shield the environment from the radionuclides.

One element of great interest is plutonium, as it can be present in various oxidation states at the same time. The knowledge on the chemical behavior of plutonium under environmental conditions is incomplete and some processes are not yet fully understood, so that experiments on plutonium chemistry are necessary for the design of a nuclear waste disposal.

At the Institute of Radioecology and Radiation Protection in Hannover, Germany, small, so called 'hot' particles on the micrometer scale are detected in sample material and extracted for experiments regarding their plutonium isotopic ratios and fission products present in spent nuclear fuel. The samples originate from Chernobyl, Ukraine, and are characterized by scanning electron microscope with energy dispersive X-ray analysis for the general elemental composition and morphology. The trace components like fission products and minor actinides are analyzed afterwards by time-of-flight (TOF) secondary-ion-mass-spectrometry, where a pulsed primary ion beam sputters the sample. The formed secondary ions are separated and detected in a Reflectron TOF mass analyzer.

The isotopic composition of major components is measured by SIMS. The dominant element in the hot particles is uranium, which can be detected without any isobaric interferences. For the elements of interest, like minor actinides and fission products, isobaric interferences are substantial and need to be suppressed. One example for an isobaric interference is U-238 masking Pu-238, which is orders of magnitude less in intensity.

The built-in TOF mass analyzer cannot resolve these isobaric interferences. Therefore, a resonance ionization laser system consisting of individually pumped titanium:sapphire lasers has been installed and coupled with the TOF-SIMS [1]. After successful initial tests on synthetic and environmental samples [2], hot particles from the Chernobyl exclusion zone were analyzed for their isotopic inventory of uranium, plutonium and americium.

Analysis of the resonance ionization behavior concerning isotopic shifts and suppression of isobaric interferences led to the result, that formerly developed ionization schemes do not fulfill the requirements of the utilized measurement setup. Adjustment of existing and development of completely new schemes for plutonium and americium were performed in collaboration with the LARISSA group at Johannes-Gutenberg University in Mainz, Germany. Results of the scheme development and corresponding hot particle analysis is presented with a focus on several influence mechanisms.

[1] Franzmann et al., International Journal of Mass Spectrometry, Volume 423, Dec 2017, Pages 27-32

[2] Franzmann et al., J. Anal. At. Spectrom., 2018,33, 730-737, DOI: 10.1039/C7JA00423K

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## Mobility of $\text{Lu}^+$ in its ground $^1\text{S}$ and metastable $^3\text{D}$ states: An ab initio study for He and Ar

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The dependence of the gas-phase mobility of an ion on its electronic state, more precisely, on the change of its interaction with a buffer gas upon electronic excitation, is known as the “electronic state chromatography” and has been studied for transition metal ions [1]. The possibility of distinguishing the ground and the metastable states of an ion by its drift times can be explored as the versatile detection scheme for ion excitation in cases when emission is impossible to observe due to low ion abundance or radiative lifetime limitations [2]. The drift path length, buffer gas, temperature and electric field strength can be tailored to a particular ion for sensitive detection of its resonance excitation frequencies. The theoretical predictions of the gas-phase transport properties based on accurate interaction potentials are invaluable to this aim [3,4].

The interaction potentials of the  $\text{Lu}^+$  ion, the lanthanide homologue of  $\text{Lr}^+$ , with He and Ar are calculated for the ground  $^1\text{S}$  and the lowest metastable  $^3\text{D}$  states by means of the coupled cluster CCSD(T) ab initio method. Transport properties are computed from the Boltzmann equation by using the accurate Gram-Charlier theory. For the ground  $^1\text{S}$  state, the room-temperature standard mobilities in the low-field limit are obtained as  $K_0 = 16.63 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$  and  $1.987 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$  for He and Ar, with the former value being in good agreement with the measured one,  $16.8 \pm 0.4 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$  [5]. Excitation to the metastable  $^3\text{D}$  state increases the mobility in He by 20% to  $19.46 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$ , while reduces it for Ar by 10% to  $\text{cm}^2\text{V}^{-1}\text{s}^{-1}$ . More accurate analysis also is performed for the mobility of the  $\text{Lu}^+$  ion in the distinct fine-structure components of the metastable state using the ab initio spin-orbit coupling potentials under different assumptions on the inelastic collision rates. The differences in the mobilities predicted can straightforwardly be distinguished experimentally

[1]. It proves the possibility of the drift time excitation detection of the  $\text{Lu}^+$  ion and indicates a good perspective of this technique for its heavier analogs [2].

This work was supported by the Russian Foundation for Basic Research (19-03-00144).

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2. M. Laatiaoui, in preparation.
3. L. A. Viehland, A. Lutfullaeva, J. Dashdorj, and R. Johnsen, Int. J. Ion Mobil. Spec. 20, 95 (2017).
4. A. A. Buchachenko and L. A. Viehland, J. Chem. Phys. 140, 114309 (2014).
5. M. J. Manard and P. R. Kemper, Int. J. Mass Spectrom. 412, 14 (2017).

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## Progresses towards a first pulsed source of cold antihydrogen in the AEGIS experiment

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The foreseen production of cold antihydrogen atoms at CERN's Antiproton Decelerator (AD) opened up the possibility to perform direct measurements of Earth's gravitational acceleration on antimatter bodies. This is one of the goals of the AEGIS collaboration: measure the value of  $g$  using a pulsed source of cold antihydrogen and a moiré deflectometer/Talbot-Lau interferometer. The milestones achieved so far by AEGIS, on the way of developing a pulsed cold antihydrogen source using resonant charge-exchange between antiprotons and cold Rydberg positronium, are presented.

First, the procedure developed to capture, manipulate and prepare a cold plasma of antiprotons for antihydrogen production is summarized. Antiprotons were captured from the AD using aluminum degraders and cooled with electrons. These mixed  $e^-/p^+$  plasma were radially compressed to sub-mm radii applying a rotating-wall drive and progressively reducing the number of cooling electrons. Antiprotons were finally transferred in high numbers to the antihydrogen production trap using an efficient in-flight launch and recapture procedure.

Second, the many milestones achieved by AEGIS in producing, manipulating and studying Ps are summarized. Ps has been first studied in a dedicated setup for spectroscopy experiments at room temperature using nanoporous silica positron-positronium converters in a reflection geometry. The spectroscopy of its 1-3 and 3-15 transitions was carried out, first showing the feasibility of AEGIS' proof-of-concept in-flight laser excitation. These experiments yielded as a byproduct the development of a long-lived source of metastable  $23\text{S}$  Ps atoms, which may be considered in the future to directly probe gravity on positronium. Ps was subsequently formed also from the 10K cryogenic converter inside the main AEGIS experiment, leading to the first Ps laser excitation to the Rydberg levels in a 1T magnetic field and to the detailed characterization of the Ps source for antihydrogen production.

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## Laser Spectroscopy of the Heaviest Actinides

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Precision measurements of optical transitions of the heaviest elements are a versatile tool to probe the electronic shell structure which is strongly influenced by electron-electron correlations, relativity and QED effects. Optical studies of transfermium elements with  $Z > 100$  is hampered by low production rates and the fact that any atomic information is initially available only from theoretical predictions. Using the sensitive RADIATION DETECTED RESONANCE IONIZATION SPECTROSCOPY (RADRIS) technique coupled to the SHIP separator at GSI, a strong optical  $^1S_0 \rightarrow ^1P_1$  ground-state transition in the element nobelium ( $Z=102$ ) was identified and characterized [1]. Furthermore, the isotopes of  $^{252,253,254}\text{No}$  were measured, revealing the isotope shift and a hyperfine splitting for the odd mass nucleus  $^{253}\text{No}$  [2]. From these measurements nuclear information on the shapes and sizes were inferred. In addition, several high-lying Rydberg levels were observed, which enabled the extraction of the first ionization potential with high precision [3].

These results will be discussed as well as the prospects for future investigations involving the study of additional nobelium isotopes and the exploration of the atomic structure of the next heavier element, lawrencium ( $Z=103$ ).

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## Bridging the spectral gap between 480-550 nm

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The ISOLDE Resonance Ionization Laser Ion Source (RILIS), is based on a dual laser system, comprised of dye and Ti:sapphire lasers. Due to the high reliability and low-maintenance requirement of solid-state lasers, efforts have been undertaken to establish ionization schemes using transitions in spectral range accessible with Ti:sapphire lasers (690 –970 nm fundamental plus 2nd, 3rd and 4th harmonics). Nevertheless, the dye lasers remain essential to the versatility of the RILIS installation, offering easy access to the wavelength range of 550-700 nm. The spectral gap between the frequency doubled Ti:Sapphire and the 532 nm pumped dye laser tuning ranges is so far only accessible with UV pumped dyes. UV pumping is inconvenient to set up, the pump power is limited to only 20 W and the UV-pumped dyes have short operating lifetimes, sometimes in the order of only several hours, and are therefore not suited for day-long on-line operation.

Here, we will present first developments towards a solid state Raman laser system, which can be pumped by the frequency doubled Ti:Sapphire laser, generating light of up to ~510 nm. This system, once fully operational, will increase the spectral range provided by the RILIS lasers and help in the exploitation of the most efficient excitation steps. Investigations into different Raman materials will be presented alongside first results demonstrating the conversion efficiency and tunability of the system.

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## Laser polarization and beta-NMR setup at CERN-ISOLDE: Developments and applications.

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In 2016, a dedicated setup for laser polarization and beta detected NMR was designed, built and commissioned on the VITO beam-line at CERN-ISOLDE[1]. This setup has seen several major upgrades during the last two years, which include a new voltage scanner design[2], a compact set of beta-detectors, a new sample handling system, a magnetic field stabilization mechanism and a new 1.2 T electromagnet. These upgrades provided a significant increase in system sensitivity and stability, with a magnetic field homogeneity on the order of parts-per-million.

One of the recent highlights was the first Na beta-NMR resonance from a liquid host[3], which makes the resolution gain of NMR in liquids finally available for beta-NMR experiments. This high-resolution liquid beta-NMR technique has been used as an ultra sensitive alternative for normal NMR spectroscopy, resulting in the first Na beta-NMR signals from biological samples.

Another first application was devoted to the polarization of  $^{35}\text{Ar}$  for weak-interaction studies[4]. Future applications include: beta-gamma correlation studies in nuclear structure and further biological applications (e.g DNA metal-ion interactions and insight into metalloproteins).

In this contribution, I will give a short introduction to laser polarization and beta-NMR, followed by an overview of the current status of the experimental setup. I will then present some of our recent results and close with an outlook on the improvements that are planned for 2019-2020.

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## High-resolution laser spectroscopy at the IGISOL: recent highlights and future goals

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Collinear laser spectroscopy is an established tool for the study of electromagnetic moments, charge radii and nuclear spins. With a history which now spans 4 decades, the technique has been successfully applied in laboratories all over the world. The Ion Guide Separator On-Line (IGISOL) features a universal production method for radioactive isotopes, making the IGISOL laboratory ideally suited to study isotopes across the chart, including in particular the refractory isotopes, actinides and lanthanides. The technical developments pursued over the past decades (the development of a radio-frequency cooler-buncher, optical pumping in the cooler-buncher, spectroscopy of doubly-charged isotopes and the development of a Cone Trap for e.g. in-vacuum optical pumping) all served to enhance the sensitivity of collinear laser spectroscopy and to enable studies of very complex atomic systems.

Recently, several upgrades were made to the collinear laser beam line at IGISOL facility. The addition of a charge exchange cell has expanded the applicability of the method significantly, and will in particular enable studies of the late d-shell species like Tc-Pd. No measurements on radioactive isotopes of these elements have been reported so far. First online experiments with the new cell have already been performed on beams of neutron-rich silver, spanning from  $^{113}\text{Ag}$  to  $^{121}\text{Ag}$ . Modifications to the cooler-buncher at the IGISOL are also underway. The goal of these upgrades is to reduce the temporal length of the ion bunches for applications in mass spectrometry. With narrower bunches a corresponding increase in the energy spread of the ions will result in a broadening of the resonance lines in collinear laser spectroscopy. This spectroscopic technique therefore presents a

unique tool to investigate the time- and energy spread of the bunches produced with the upgraded cooler-buncher.

In this contribution, the recent laser spectroscopy measurements on radioactive beams of silver will be discussed. Offline tests on the newly upgraded cooler-buncher will also be examined. Finally, plans for a new laser resonance ionization spectroscopy apparatus, tailor-made for the many challenging atomic systems that so far have eluded optical spectroscopy, will be presented. All these topics are part of the continuation of a long tradition in technical innovations in laser spectroscopy at the IGISOL. The implications for the future physics program will be explored in some detail, focusing in particular on the refractory elements with  $42 < Z < 47$ .

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## Low Q-value measurements with the PI-ICR technique at JYFLTRAP

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The determination of the absolute scale of the neutrino mass is one of the biggest challenges in fundamental physics. In low-energy nuclear physics electron neutrinos are studied via weak interaction processes such as beta decay and electron capture. The full energy released in a decay, the Q-value, can be deduced with high precision mass spectrometry by measuring the mass difference between the parent and the daughter nuclei. Comparing that to the endpoint of the electron spectrum, any missing energy can be related to the neutrino mass. Different installations are investigating this, e.g. the KATRIN experiment [1] in Karlsruhe, Germany, focusing on the tritium beta decay, or the ECHo collaboration [2] analyzing the energy spectrum following the electron capture process of  $^{163}\text{Ho}$ .

Beta decays can proceed to nuclear excited state in the daughter nucleus. There are several possible cases where the decay can potentially proceed to a state with a very low Q-value, i.e. less than 100 eV [3]. In such a case a bigger fraction of the decay energy is in the form of the neutrino mass and also the expected skewedness of the beta endpoint spectrum will be smaller.

We have measured the Q-values of the following candidates  $^{135}\text{Cs}(7/2+) \rightarrow ^{135}\text{Ba}(11/2-, 1/2+)$  and  $^{111}\text{In}(9/2+) \rightarrow ^{111}\text{Cd}(3/2+)$  with the JYFLTRAP Penning setup located at the IGISOL facility, Jyväskylä, using the phase-imaging ion-cyclotron resonance (PI-ICR) method [4]. Preliminary results on the Q-value measurements performed will be presented.

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## CP-violating electron electric dipole moment enhancement factors in the BaOH and YbOH molecules.

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New CP (Charge conjugation and spatial Parity) violations absent in the Standard Model are assumed to be responsible for the large surplus of matter over antimatter in the universe [1]. They could be observed in ordinary matter through a set of interactions violating both parity and time-reversal symmetries (P, T odd), such as the electron Electric Dipole Moment (eEDM). Thus, a non-zero eEDM experimental evidence would be a probe of new physics.

Recent paper [2] pointed out that triatomic molecules isoelectronic to the laser coolable diatomic molecules employed for the search of P, T-odd interaction constants could exhibit the same sensitivity to CP-violation, laser coolability as well as an advantageous vibrational structure that could further improve the experimental precision.

In this work, we calculate the eEDM molecular enhancement factor, essential for the interpretation of the experimental measurements, in the BaOH and YbOH molecules and make a direct comparison with the analogue diatomics BaF and YbF.

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## Ground state and decay properties measured with the FRS Ion Catcher

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At the FRS Ion Catcher [1] at GSI/FAIR, projectile and fission fragments are produced at relativistic energies, separated in-flight, range-focused, slowed-down and thermalized in a cryogenic stopping cell. Thereby cooled beams of high purity can be provided. These beams are transmitted to a

multiple-reflection time-of-flight mass spectrometer (MR-TOF-MS), which achieves mass resolving powers beyond 600,000 (FWHM), high transmission efficiency, ion capacities of more than a million ions per second, and cycle frequencies as high as 1 kHz. The MR-TOF-MS can perform direct mass measurements of exotic nuclei and provide an isobarically and even isomerically clean beam [2].

More than 30 short-lived ground state masses have been measured with high mass accuracies (uncertainties down to  $6 \cdot 10^{-8}$ ). For seven nuclides, this constitutes the first direct mass measurement. The measured two-neutron separation energies and their slopes near and at the  $N=126$  shell closure indicate a strong element-dependent binding energy of the first neutron above the closed proton shell  $Z=82$ . The experimental results deviate strongly from the theoretical predictions [3].

Besides these “conventional” mass measurements, a novel method for the simultaneous and direct measurements of masses, half-lives, decay branching ratios and isomer excitation energies of exotic nuclei has been demonstrated with the system. For these measurements, the CSC is used as an ion trap for mother and daughter nuclei, and the MR-TOF-MS identifies and counts these isotopes. The feasibility of the method was demonstrated in experiments employing the alpha decay of  $^{216}\text{Po}$  and the isomer-to-ground transition in  $^{119\text{m}}\text{Sb}$ . In the future, the method will be used to measure beta-delayed neutron emission probabilities.

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## First online laser ionized Ac beam at ISOLDE

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Over the past decades, resonant ionization laser ion sources have become the workhorse for the selective and efficient production of radioactive ion beams using Isotope Separator On-Line (ISOL) technique. However, the list of ion beams that have been produced at CERN-ISOLDE was limited to 70 different elements of which about 40 are laser ionized. Recently, Ac has been added to this list. The online production of actinium ion beams showed to only be possible with use of the hot cavity laser ion source at CERN-ISOLDE. The production of Ac beams at CERN-ISOLDE will be translated to the CERN-MEDICIS facility, where medical isotopes, e.g.  $^{225}\text{Ac}$ , will be produced and collected for medical research [1]. New opportunities, such as in-source laser spectroscopy, are also now open to extend the current knowledge on these isotopes [2]. Results on the ion beam production of Ac isotopes, showing the importance of the laser ion source, will be presented.

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## Latest Results of the High-Precision Penning-Trap Mass Spectrometer PENTATRAP

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Currently, the Penning-trap mass spectrometer PENTATRAP [1] at the Max-Planck-Institut für Kernphysik in Heidelberg is performing first mass-ratio measurements with a relative uncertainty in the  $10^{-11}$  regime using highly charged ions of stable xenon isotopes. In this uncertainty regime the near future mass measurements of dedicated nuclides will allow, among others, to contribute to tests of special relativity [2], bound-state QED [3] and neutrino-physics research [4, 5].

Achieving this level of precision requires using a cryogenic detection system with single ion sensitivity [6] and phase sensitive Fourier Transform Ion Cyclotron Resonance (FT-ICR) image-current detection methods [7] in combination with highly charged ions provided by external electron beam ion traps. A unique feature of PENTATRAP is the suppression of systematics by performing simultaneous measurements in two adjacent traps of our five-trap tower, which, according to our latest measurements, are subject to equal fluctuations of the magnetic field [8].

The talk will present the experimental setup of PENTATRAP and the recent measurement results.

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## Trapping and manipulation of atomic and molecular ions

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In the recent past, the ability to control and manipulate trapped ions at the quantum level have gone through an amazing evolution. Based on laser cooling of trapped atomic ions, investigations of a

wide range of fundamental quantum physics phenomena have been made possible, and today, laser-cooled and trapped ions constitute one of the most successful platforms for the quantum technology as well as optical atomic clock developments. Recently, the methods used to control and manipulate atomic ions has furthermore attracted attention from researchers interested in cold molecular science due to the potential of investigating the structure and internal dynamics of molecules at an unprecedented level of accuracy, as well as the prospects of studying Chemistry in unexplored cold and ultracold regimes. This field of research is still in its infancy, but holds great promises for the future.

In the tutorial, I will discuss various aspects of trapping and manipulation of atomic and molecular ions in this context.

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## Direct frequency-comb-driven Raman transitions in the terahertz range

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In this contribution, I will present our recent results on the use of a femtosecond frequency comb to coherently drive stimulated Raman transitions between terahertz-spaced atomic energy levels [1]. More specifically, we address the 3d 2D<sub>3/2</sub> and 3d 2D<sub>5/2</sub> fine structure levels of a single trapped <sup>40</sup>Ca<sup>+</sup> ion and spectroscopically resolve the transition frequency with a relative accuracy of 5.5x10<sup>-12</sup>. The achieved accuracy is nearly a factor of five better than the previous best Raman spectroscopy of the same transition [2], and is currently limited by the inaccuracy of our atomic clock reference. Using direct frequency comb Raman spectroscopy on four other isotopes <sup>42,44,46,48</sup>Ca<sup>+</sup>, in combination with precise measurements of the 4s 2S<sub>1/2</sub>-3d 2D<sub>5/2</sub> transition, we were also able to improve bounds on new physics beyond the standard model [3,4].

Furthermore, I will discuss the population dynamics of frequency-comb-driven Raman transitions which can be fully predicted from the spectral properties of the femtosecond frequency comb. We achieved Rabi oscillations with a contrast of 99.3(6) % and milliseconds coherence time, i.e., similar contrast as have previously achieved in the GHz-range [5].

Perhaps most importantly, the technique can be easily generalized to Raman transitions in the sub-kHz to tens of THz range and should be applicable for driving, e.g., spin-resolved rovibrational transitions in molecules and hyperfine transitions in highly charged ions.

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## Precision Laser Spectroscopy of a magnetic dipole fine structure transition with a single <sup>40</sup>Ar<sup>13+</sup> ion at ALPHATRAP

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The Penning-trap experiment ALPHATRAP was initially purpose-built for high-precision measurements of the bound electron  $g$ -factor in heavy highly charged ions (HCI). HCI are excellent candidates to test bound-state quantum electrodynamics (BS-QED). In the vicinity of the nucleus the strongest electromagnetic fields can be found, which allow for tests of QED under extreme conditions.

In addition the current experimental setup already has also capabilities for laser spectroscopic investigations on such systems. Depending on the nuclear charge and electronic charge state of the HCI the energies of M1 transitions within a fine structure or even a hyperfine structure multiplett are shifted into the optical regime. Measuring such transitions constitutes a stringent test on BS-QED calculations including relativistic many body calculations as well as nuclear contributions.

Those fine structure and hyperfine structure transitions are electric dipole forbidden and correspondingly narrow and show a strongly suppressed sensitivity to external perturbations, which makes HCI interesting candidates for an envisaged use in high-precision metrology or as optical frequency standards. Furthermore transitions in HCI can show a strongly enhanced sensitivity for possible variations of fundamental constants, such as the fine structure constant  $\alpha$ , which would indicate physics beyond the Standard model. Conversely the very long lifetimes of the transitions can impose delicate experimental challenges since in many cases the transition frequencies are only known to insufficient precision, which can make it difficult to locate them via fluorescence-based detection. We present a novel method that is independent of fluorescence and which allows rapid finding of those narrow transitions by using the continuous Stern Gerlach effect in a double Penning trap. By using this technique the magnetic moment projection value of the ion, depending on the electronic configuration, onto the axis defined by the magnetic field of the ion can be determined. If a transition between two states with different projection values is induced by the laser, it is possible to detect this change in the projection value in the ions axial motional frequency and no need arises to observe fluorescence photons.

Using this method we have recently performed laser spectroscopy of the magnetic dipole (M1)  $2p\ ^2P_{1/2} - ^2P_{3/2}$  fine structure transition using a single  $^{40}\text{Ar}^{13+}$  ion stored in the cryogenic Penning-trap system of the ALPHATRAP  $g$ -factor experiment at the Max-Planck-Institut für Kernphysik. An overview of the experiment and recent results will be presented.

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## LISEL@DREAMS –The future of Accelerator Mass Spectrometry

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LISEL (Low energy Isobar SEparation by Lasers) is a future project at the DREAMS (DREsden Accelerator Mass Spectrometry) facility to widen the applications of AMS by extending the range of measurable (radio-) nuclides.

AMS has proven to be a versatile tool capable of detecting a large number of long-lived radionuclides at the ultra-trace level –i.e. isotope ratios down to  $1\text{E-}16$ . However, being a mass spectrometric method, it is limited by the presence of strong isobaric background. To overcome this limitation, we propose to remove the isobars already at the low-energy side by laser photodetachment. This method allows to selectively neutralize isobars by laser radiation, leaving the ions of interest intact. First studies were performed at the University of Vienna and gave promising results [1,2] for the easier to be measured low-mass AMS isotopes Al-26 and Cl-36.

Within the LISEL project this method will be for the first time applied to an AMS facility based on a 6 MV tandem accelerator. The first isotopes to be addressed with the new method will be Mn-53 and Fe-60. Both are currently only measurable at AMS facilities with more than 10 MV terminal

voltage (currently available only at the ANU in Canberra/Australia or the LMU and TU Munich in Garching/Germany). Further on we foresee to apply this method to other rare isotopes, making LISEL@DREAMS a versatile machine for “all” isotopes. This will subsequently widen the applications and also the user community.

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## Negative Ions Studies in the Frankfurt Low Energy Storage Ring (FLSR)

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In order to allow for studies of the electronic structure of negative atomic and molecular ions by laser photodetachment, a commercial rf charge exchange ion source for negative ions (Alphatross®, National Electrostatic Corporation [1]) has been installed at the injection terminal of the Frankfurt Low Energy Storage Ring (FLSR) facility [2]. First tests with negative ions stored in FLSR at 20 keV have successfully been conducted. So far, the storage times of 50 nA He<sup>-</sup>, 260 nA O<sup>-</sup> and 110 nA OH<sup>-</sup> have been measured. They are in good agreement with the theoretical predicted storage times based on the residual gas pressure ( $p[\text{FLSR}] \sim 1,0 - 2,0 \times 10^{-10}$  mbar, corrected for H<sub>2</sub> as residual gas). Also, the measured lifetime of the metastable He<sup>-</sup> of about 300 us is in good agreement with previous measurements [3].

In a next step photodetachment of the stored ions with tunable laser beams in the VIS and NIR range will be performed. To achieve this, viewports have been installed in the long section of the ring. One window allows overlapping the laser and ion beam longitudinally whereas two windows were installed at the interaction point on the long section. The high particle density at this position allows a perpendicular overlap of the laser and ion beam and thus minimizing the doppler shift seen by the moving ions. The detached neutrals can be detected by position sensitive silicon strip detectors mounted after the long section of the ring.

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## Laser resonance ionization of lanthanides, or can we reach 200% ionization efficiency?

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For last several years, the research activity of the workgroup LARISSA of the Mainz University are focused on resonance ionization spectroscopy of rare-earth elements. Beside the pure scientific interest, to investigate their atomic structure, ionization potential, or to determine their auto-ionizing states, the work was aimed for the development of highly efficient laser resonance ionization schemes for lanthanides, whose radioisotopes are of high interest for fundamental (ECHO project) and for applied (MEDICIS project) researches. Laser resonance ionization spectroscopy was accomplished almost for all lanthanides, with a particular focus on holmium, erbium, and lutetium. It was performed using the all-solid-state Titanium:sapphire laser system of the Mainz University design, and obtained results have surpassed the best expectations.

The newly developed two-step laser resonance ionization schemes clearly showed a high ionization efficiency far above 50 %. As it has a notable potential to be applied to radioactive ion beam facilities, e.g. to the CERN-MEDICIS facility, it became necessary to verify the results. Additional investigations were undertaken to demonstrate the congruence of ionization efficiency values via gamma-spectroscopy before and after the measurement run. In this report, the results of resonance ionization spectroscopy and ionization efficiency measurements are going to be presented. The use of the developed laser ionization schemes at the MEDICIS facility to provide a regular production of innovative medical radioisotopes will be discussed.

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## Precision spectroscopy of "hot" molecules at CRIS-ISOLDE/CERN

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Molecules containing heavy and deformed radioactive nuclei are predicted to provide enhanced sensitivity to explore nuclear electroweak structure as well as to test the violation of fundamental symmetries. However, experimental measurements of such radioactive systems are scarce, and in most of the cases, quantum-chemistry calculations constitute the only source of available information. This contribution will discuss recent achievements in precision laser spectroscopy of radioactive molecules from the Collinear Resonance Ionization Spectroscopy (CRIS) experiment at ISOLDE-CERN. The first ever laser spectroscopy of radiogenic molecules (RaF) will be presented.

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## Collinear laser spectroscopy of Pd and Yb at the IGISOL facility

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Collinear laser spectroscopy is a powerful tool for the study of properties of exotic nuclei via the measurement of hyperfine structure and isotope shift. This technique has been in use at the IGISOL facility, University of Jyväskylä, for over 20 years [1]. During this time, the primary focus has been on studies using ionic transitions, either from the ionic ground state or from metastable states populated via optical pumping in the radiofrequency quadrupole cooler-buncher [2]. With a specific focus on yttrium, doubly-charged ions have also been studied [3]. Additionally, until 2019, all laser spectroscopy at the collinear laser facility in Jyväskylä has been conducted using a continuous wave (cw) dye laser.

In the last year, a new charge-exchange cell has been installed to afford access to fast atomic beams in order to expand the region of elements that can be studied. This was commissioned online using neutron-rich isotopes of Ag, to be presented elsewhere in this conference. Most recently, a cw Ti:sapphire Matisse laser and frequency doubling unit have been taken into use, complementing the wavelengths accessible with the cw dye laser.

The cw Ti:sapphire laser has been primarily used for systematic studies for frequency determination using saturation absorption spectroscopy [4]. Now, it has also been implemented for collinear laser spectroscopy using an ionic transition in ytterbium, with all stable isotopes measured. These tests serve as a comparison between different methods to frequency-stabilise the laser, namely either via a WSU10 wavemeter or via a transfer cavity. The next step has been to combine the charge-exchange cell and both the cw dye and Ti:sapphire lasers for offline studies of stable palladium isotopes in preparation for an experiment on radioactive Pd isotopes. Several transitions from different metastable atomic states populated in the charge-exchange process have been tested, as well as the ground state transition which is accessible with the dye laser.

In this contribution the results from commissioning the cw Ti:sapphire laser using collinear laser spectroscopy of stable Yb isotopes will be presented, including a conclusion on the reached accuracy and precision of the different methods for frequency stabilisation. The comparison between different atomic transitions and the chosen one(s) for online use in palladium isotopes will also be discussed and the physics motivation behind the study of the neutron-rich isotopes will be presented.

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## Enhanced ion thermalization with the cryogenic buffer-gas stopping cell of SHIPTRAP

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The existence of the heaviest elements is crucially connected to nuclear shell effects, which counteract spontaneous fission and determine the stability of such exotic systems. Penning-Trap Mass Spectrometry (PTMS) is a suitable technique, which allows the investigation of shell effects and their evolution for nuclear systems with different proton to neutron ratios through direct and highly-precise measurements of the atomic masses and the nuclear binding energies.

During summer 2018 direct mass measurements of transfermium nuclides  $^{251}\text{No}$  ( $Z=102$ ),  $^{254}\text{Lr}$  ( $Z=103$ ) as well as the superheavy nuclide  $^{257}\text{Rf}$  ( $Z=104$ ) have been successfully achieved, for the first time, with the SHIPTRAP mass spectrometer. Such challenging experiments face the problem of very low production rates, down to few ions per day and demand a very efficient ion preparation and manipulation together with high detection sensitivity and resolving power. In particular the ions need to be thermalized after production via fusion-evaporation reaction and separation through the SHIP velocity filter and prior to be transferred to the Penning traps. Thermalization is the most crucial step. It is achieved by slowing down the ions into a buffer-gas stopping cell. In this talk the latest optimizations of the recently implemented SHIPTRAP cryogenic buffer-gas stopping cell and its enhanced performance in terms of efficiency and purity will be presented.

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## Source Development and Simulations of Ion Optics for an Ion Source providing slow highly charged Th-229m ions

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$^{229\text{m}}\text{Th}$  became a nuclide of high interest in the field of quantum physics in recent years<sup>[1]</sup>. Experiments have shown that it is a promising candidate for the development of a nuclear clock<sup>[2][3]</sup> and it promises to contribute to the search for physics beyond the standard model<sup>[4]</sup>. At the moment, the only experimental access to  $^{229\text{m}}\text{Th}$  is via  $\alpha$  decay of its mother nuclide  $^{233}\text{U}$ , which proceeds through the isomeric state in 2% of all decays. The aim of the Mainz based collaboration TACTICa (Trapping And Cooling of Thorium Ions with Calcium) is to capture  $^{229}\text{Th}$  and further isotopes of thorium inside a mixed ion crystal with  $^{40}\text{Ca}^{+}$  in a Paul trap for precision spectroscopy. This has successfully been demonstrated with  $^{232}\text{Th}^{+}$  ions<sup>[5][6]</sup>. The segmented Paul trap is capable to capture ions with kinetic energies of up to 1 keV. The capture of  $^{229}\text{Th}$  recoils is a challenge, as the recoil ions from the decay of  $^{233}\text{U}$  have a kinetic energy of  $\leq 84$  keV in a wide range of charge states<sup>[7]</sup>. Whereas in [2, 3],  $^{229}\text{Th}$  has been successfully extracted as low-energy ion beam from a buffer-gas-stopping-cell based setup, this approach cannot be used for deceleration in our setup, because residual gas would affect the precision of spectroscopy and lead to a fast decay of highly charged states. Therefore, a novel ion source is currently being developed, which will be able to provide low-energy  $^{229\text{m}}\text{Th}$  ions produced as recoil daughter products in the  $\alpha$  decay of  $^{233}\text{U}$ .

Complementary, a laser-ablation source<sup>[5]</sup> will be installed to provide other Th isotopes. The combination of ablation- and recoil source will allow for studying a variety of Th isotopes for fundamental studies<sup>[8]</sup>. Simulation data for the development of the source as well as simulations of the ion beam, spectra of the <sup>233</sup>U source and a first design of the ion source will be presented.

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## Determination of the Electron Affinity of Cesium

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In negative ions the correlated motion of the valence electrons are pronounced and experimental investigations can therefore serve to benchmark theoretical models that go beyond the independent particle model [1]. In such studies the Electron Affinity (EA) is the only atomic property that can be measured with high resolution. One of the most commonly used methods to measure EAs is Laser Photodetachment Threshold Spectroscopy (LPTS) in which the onset of the photodetachment [1] process is observed at an energy corresponding to the EA of the element. However, the EA of negative ions with an s-valence electron cannot be measured with high precision using LPTS since the onset at the threshold, according to the Wigner law, is not sharp [2]. This problem can be circumvented by observing the onset of the photodetachment process when the residual atom is left in an excited state, where a sharp threshold will be obtained if the residual atom is left in a p-state. This can be achieved by detecting the residual excited atom using the technique of Resonance Ionization Spectroscopy (RIS) [3].

In the present work, a high resolution measurement of the EA of cesium will be presented in which a refined RIS scheme has been applied to detect the excited state residual Cs atoms. In the experiment, negatively charged cesium ions are produced in a cesium sputter source, accelerated to 6 keV, mass selected and finally merged with two pulsed laser beams over a 70 cm interaction region. The first laser photodetaches the negative cesium ions, leaving the residual cesium atom in the Cs(6p j=3/2) state. The second laser beam thereafter excites the Cs(6p j=3/2) atoms to the Cs(25s) Rydberg state. The Rydberg atoms will after the interaction region enter a field ionizer where they are first ionized in a strong electric field and then decelerated by 1.5 keV. Positive ions produced by collisional detachment in the interaction region will, on the other hand, keep their kinetic energy as they pass the field ionizer. Hence, the signal and background ions can be separated in an electrostatic analyzer placed after the field ionizer and finally detected as two spatially separated spots on a Position Sensitive Detector (PSD).

By scanning the laser used for photodetachment over the opening of Cs(6p j=3/2) channel, we were able to perform state selective LPTS with a sharp onset of the photodetachment process. By using both co- and counter propagating alignments of the photodetaching laser beam the Doppler shift was compensated to all orders. An improved value of the EA of Cs will be presented at the conference.

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## U isotopic shifts and hyperfine analysis using tunable laser spectroscopy of laser ablation plumes

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Rapid and stand-off detection of isotopes is ultimately important for numerous applications including nuclear nonproliferation monitoring and forensics. Optical spectroscopy in conjunction with laser-produced plasma (LPP) is a very promising tool for in-field and non-contact isotopic analysis of solid materials. Both emission and fluorescence spectroscopy of laser ablation plumes can be used for isotopic analysis. However, the reported isotopic shifts of U I and U II transitions in the visible spectral regime are in the range ~ 1-25 pm which necessitate the requirement of an extremely high-resolution spectrograph for using emission based diagnostic tools (eg. laser-induced breakdown spectroscopy) for isotopic analysis. In addition to this, the emission spectral analysis requires thermal excitation by electrons which happen at early times of plasma evolution when the lines are broader due to various line broadening mechanisms (Stark, Doppler etc.). Laser-absorption/ laser-induced fluorescence spectroscopy (LAS/LIFS) can be used to marginalize the effect of instrumental broadening. LAS and LIFS probe the ground state atoms existing in the plasma when it is cooler, which inherently provides narrower lineshapes. We recently reported the linewidths of U transitions using LAS/LIFS of laser-produced plasmas are ~ 1 pm which is significantly lower than the average isotopic shift of U atoms/ions (~ 9 pm). In addition to isotopic splitting, the hyperfine structures (hfs) may influence the lineshape of a transition. Hyperfine splittings are usually small; however, in certain cases, they can be larger than isotope splitting. In that scenario, isotope shifts of atoms and molecules can be entangled with hyperfine structure. We studied the isotopic shifts between <sup>238</sup>U and <sup>235</sup>U transitions and hyperfine structures of <sup>235</sup>U using LIF and LAS of laser-ablation plumes. The collinear excitation scheme for stand-off isotopic analysis, the accuracy of isotopic ratios and its correlation to plume dynamics, radiation transport will also be discussed.

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## Collinear laser spectroscopy at ISOLDE-CERN: COLLAPS's recent results and perspectives

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on behalf of the COLLAPS collaboration.

Since the 1980s, high-resolution laser spectroscopy has been used at the COLLAPS beam line at ISOLDE-CERN to study the structure, size and shape of radioactive nuclei [1,2]. By probing the atomic hyperfine structure and isotope shifts, nuclear moments and mean-square charge radii can be extracted and nuclear spins can unambiguously be determined. These fundamental properties provide key insights in the nuclear structure far from stability and its evolution along an isotopic chain, as will be illustrated by some recent highlights of COLLAPS in the Ni ( $Z = 28$ ) and Sn ( $Z = 50$ ) regions.

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## Collinear Laser Spectroscopy meets Ion-Trap accuracy: Recent developments in the $\text{Ca}^+$ puzzle

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High-precision ion-trap measurements of the isotope shift in the  $4s \rightarrow 4p$  doublet of  $\text{Ca}^+$  have shown a significant deviation from theory regarding the ratio of the two field-shift constants [1]. To gain more insight into this puzzle, the  $6s \rightarrow 6p$  doublet in  $\text{Ba}^+$  has been investigated with high-precision collinear laser spectroscopy [2]. Here, the measurements of the rest-frame transition frequencies have reached a precision comparable to ion-trap measurements on this and similar electric-dipole transitions. However, in this case the field-shift ratio is clearly smaller than estimated by the hydrogenic solution and has been reproduced by theory within a  $2\sigma$ -range. This even deepens the  $\text{Ca}^+$ -puzzle and, therefore, collinear laser spectroscopy is currently performed on the  $\text{Ca}^+$  transitions at our KOALA beamline. We aim for a similar or even better precision compared to the trap measurements [1] to verify the results that lead to the puzzling observation. An overview of the  $\text{Ba}^+$  measurements as well as recent developments and results of the  $\text{Ca}^+$  campaign will be presented in this contribution. This work was supported by BMBF under contract 05P19RDFN1 and HGS-HIRE.

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## Spectroscopic analysis of radioactive strontium with low isotopic abundance using laser resonance ionization

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Strontium-90 ( $^{90}\text{Sr}$ ) is one of the major fission products released in the Fukushima Daiichi Nuclear Power Plant accident in Japan. Due to its long half-life of 28.8 years and similar biochemical behavior to calcium,  $^{90}\text{Sr}$  tends to accumulate in human bones causing long-term internal exposure. The food contamination standard in Japan is set to be 100 Bq/kg, which corresponds to  $^{90}\text{Sr}$  isotopic abundance in marine samples of the order of 1 ppb or less.

Resonance ionization technique using narrow linewidth lasers is suitable for analysis requiring high elemental and isotopic selectivity. In general, there is a trade-off relation between isotopic selectivity and transition efficiency for a specific resonant transition. High isotopic selectivity is expected for a transition with a narrow natural width, but a high power laser is required for saturation.

In this study, we have investigated on two types of three-step resonance ionization schemes of Sr: (A) 460.9 nm - 655.2 nm - 426.3 nm and (B) 689.4 nm - 487.4 nm - 393.8 nm. Both schemes excite Sr atoms to the same autoionization level. The difference lies in the 1st transition from the ground state; the 460.9 nm line is an E1 allowed transition and the 689.4 nm line is a semi-forbidden intercombination transition with natural widths of 32 MHz and 7.5 kHz, respectively. An external cavity diode laser (ECDL) with a narrow bandwidth (about 0.3 nm) interference filter has been developed for the 689.4 nm transition. This ECDL has better long-term stability against angular misalignment than the conventional Littrow-type ECDL with a diffraction grating.

In the presentation, we will show the results on resonance ionization spectroscopy of  $^{90}\text{Sr}$  and Sr stable isotopes via schemes (A) and (B) under various sample conditions. Optical isotopic selectivity will be evaluated for each scheme and application of resonance ionization spectroscopy to the analysis of  $^{90}\text{Sr}$  in marine samples will be discussed.

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## Approaching the N = 20 Island of Inversion: Precision Mass Measurements of Neutron-Rich Ne Isotopes

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To better understand nuclear structure, precision mass spectrometry of radioactive beams is required. Nuclides of interest become short lived and production rates drop further from stability. Additionally, these beams are frequently contaminated with both isobars and molecules which can obscure high-precision measurements. To help overcome these challenges, the Multiple-Reflection Time-of-Flight Mass Spectrometer (MR-TOF-MS) was commissioned at TRIUMF's Ion Trap for Atomic and Nuclear science (TITAN). This device is capable of both beam purification, through mass selective re-trapping, and fast, precise, high-sensitivity mass measurements. Furthermore, these two different modes of operation can be used sequentially enabling measurements to be done in exceedingly contaminated beams. Additionally, the technique of collision induced dissociation has been investigated to enhance the suppression of molecular contamination by an order of magnitude. These capabilities were demonstrated during the mass measurements of neutron-rich  $^{24-26}\text{Ne}$  in which precisions of approximately  $10^{-7}$  were achieved. These isotopes are part of the chain of Ne isotopes approaching the "island of inversion" and crossing the N = 20 isotone which motivates further measurements in this region.

## Penning-Trap Mass Spectrometry of the Heaviest Elements beyond $Z=100$ with SHIPTRAP

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Superheavy elements ( $Z \geq 104$ ) owe their very existence to an enhanced stability resulting from nuclear shell effects. Direct high-precision Penning-trap mass spectrometry (PTMS) in this region can provide indispensable knowledge on the nuclear binding energy of these elements. This will eventually help to constrain theoretical predictions for the so-called island of stability, a region of long-lived nuclides expected around  $Z = 114 - 126$ ,  $N = 184$ . However, due to their low production rates, PTMS of these elements requires the highest levels of efficiency and sensitivity. In a beam-time campaign at GSI Darmstadt in 2018, recent developments at SHIPTRAP allowed us to extend PTMS to heavier and more exotic nuclides with production rates as low as one ion per minute. For the first time, direct mass spectrometry of  $^{251}\text{No}$ ,  $^{254}\text{Lr}$  and the superheavy nuclide  $^{257}\text{Rf}$  ( $Z = 104$ ) were performed using the Phase-Imaging Ion-Cyclotron Resonance technique. The latter allowed to directly resolve the low-lying isomeric states  $^{251m,254m}\text{No}$  and  $^{254m,255m}\text{Lr}$  from their ground states. In this contribution an overview of the recent measurements will be given.

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Following earlier studies of the Zn ( $Z = 30$ ) and Ga ( $Z = 31$ ) isotopic chains [1, 2, 3, 4], the nuclei of germanium ( $Z = 32$ ) can provide a useful insight into the nuclear shell evolution of the  $N = 40$  subshell closure by adding protons beyond the  $Z = 28$  closed shell. At the same time, the inverted odd-even staggering effect observed for the first time on Kr ( $Z = 36$ ), Rb ( $Z = 37$ ) and Sr ( $Z = 38$ ) [5] and recently also on Ga isotopes [6], makes the Ge isotopic chain a good case to study the evolution of this phenomenon as the proton number increases.

Using the collinear laser spectroscopy technique at the COLLAPS beamline located at ISOLDE-CERN, the hyperfine spectra of the  $^{68-74}\text{Ge}$  around  $N = 40$  were probed in order to extract nuclear spins, electromagnetic moments and changes in the mean-square charge radii. For this study, the  $4s^2 4p^2 \ ^3P_1 - 4s^2 4p5s \ ^3P_1$  (269 nm) atomic transition of Ge atom was used. The production of laser light with this wavelength is challenging with cw Ti:Sa and dye lasers and required the installation of a frequency mixing unit. In this contribution, preliminary results of the ground state structure of  $^{68-74}\text{Ge}$  will be presented together with details of the newly installed laser system.

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## Recent studies for nuclear structure and astrophysics at JYFLTRAP

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The Ion Guide Isotope Separator On-Line (IGISOL) facility in the JYFL Accelerator Laboratory offers versatile possibilities for high-precision mass measurements with the JYFLTRAP Penning trap mass

spectrometer. In this contribution, recent measurements performed at JYFLTRAP for nuclear structure and astrophysics are reviewed. These include for example measurements on neutron-deficient nuclei close to  $A=80$ , neutron-rich rare-earth isotopes close to  $N=100$  as well as nuclides close to  $^{78}\text{Ni}$ . In addition to the ground states, information on long-living isomeric states has been obtained. Many of the studied nuclides were measured for the first time and therefore provide essential information for nuclear structure far from stability as well as for nuclear astrophysics.

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## Collinear laser spectroscopy of nickel isotopes at CERN-ISOLDE –First application of the new data acquisition system TILDA at COLLAPS

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Nickel isotopes  $^{58-68,70}\text{Ni}$  were measured using bunched-beam collinear laser spectroscopy at the COLLAPS setup at CERN-ISOLDE with a newly developed time-resolving data acquisition system. Nickel has the magic proton number 28, the first magic number that arises due to the spin-orbit interaction, and the isotope chain is a benchmark for nuclear structure theory. Of particular interest are recent ab-initio calculations entering into the medium mass region and demonstrating a clear correlation between the charge radius, the neutron radius and the electric dipole polarizability  $\alpha_D$  in the case of  $^{48}\text{Ca}$  [1] which could be confirmed in a recent experiment [2].

Data of nickel isotopes were taken at COLLAPS in two beamtimes with the first application of the new data acquisition system TILDA [3], developed at the TRIGA laser experiment [4] and then transferred to COLLAPS. TILDA allowed a better control of the experiment and improved the consistency of the measured data, since the temporal structure of the ion bunches is directly observable



and is stored for off-line analysis [3,5]. Thereby an overfilling of ISCOOL, the radio frequency cooler and buncher at ISOLDE, can be directly identified in the temporal structure of the bunches by an increase of the temporal bunch length, a time dependency of the resonance indicating different velocity classes within the bunch and a shifted mean velocity of the ions.

Our measurements of the mean-square charge radii up to  $N=42$  shed light on the effect of the sub-shell closure around  $N=40$  and help to understand its  $Z$  dependence in relation to neighboring isotopic chains.

This work was supported by BMBF under contract 05P19RDFN1 and 05P18RDCIA.

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## RILIS Laser Ion Source Development for ISOL Systems at RISP

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The Resonance Ionization Laser Ion Source (RILIS) system has been developed for the future on-line laser ion source for a new heavy ion accelerator, RAON, in Korea. A tunable laser system consisting of four Ti:Sapphire lasers pumped by a Nd:YAG laser has been set up for application in the RILIS laser ion source development in the ISOL facility of the Rare Isotope Science Project (RISP)/IBS. As a milestone of extraction of rare isotopes produced through uranium fission, double magic nucleus of Sn-132 is our first target. Three step resonant ionization schemes with four laser lights, at 286 nm, 301 nm, 811 nm and 823 nm, have been tested for Sn and the relative ionization efficiencies have been investigated using the reference cell for the laser resonance ionization scheme development. In particular, a method to improve the ionization efficiency with four-color laser ionization scheme assisted by multiphoton Raman transition is introduced [1]. In the presentation, we present the recent results and the current status of the hot-cavity type laser ion source development in the off-line ion source test facility of RISP, including measurements of ionization efficiency, emittance and mass resolving power.

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## Highly selective two-step laser ionization schemes for analysis of actinide mixtures

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In the context of investigations required for the long-term storage of radioactive waste, the determination of ultra-trace amounts of actinide elements in environmental samples as well as the study of their chemical and migration properties are very important. The SIRIUS project, a collaboration of IRS (Institut für Radioökologie und Strahlenschutz) Hannover, IPH (Institut für Physik) Mainz and KCh (Institut für Kernchemie) Mainz, focuses on spatially resolved ultra-trace imaging of actinide distributions on surfaces and environmental particles. The experimental approach is based on laser resonance ionization mass spectrometry (RIMS) [1] on sputtered neutral particles in combination with efficient time-of-flight mass spectrometry. For this technique, efficient and highly element selective laser ionization schemes are required for each element under study. In the past, three-step ionization processes applying three well-tuned laser beams were used for ultra-trace analysis of uranium, plutonium, and technetium.[2] In order to simplify the experimental effort, to extend the RIMS capabilities to further relevant minor actinides and to enable fast switching between the different actinide elements within one sample, two-step ionization schemes have been developed at Mainz University. With the use of, automated grating assisted Ti:sapphire lasers featuring intra-cavity SHG, the two-step ionization processes allow for a fast change of the ionization scheme and therefore the element of interest during the measurement while preserving most of the specifications of more complex arrangements.[3] New ionization schemes were tested with regard to overall detection efficiency and elemental selectivity using synthetic actinide mixtures containing realistic ratios of  $10^{16}$  uranium atoms ( $^{235}\text{U}$  and  $^{238}\text{U}$ ),  $10^{13}$  americium atoms ( $^{241}\text{Am}$  and  $^{243}\text{Am}$ ) and  $10^{12}$  plutonium atoms ( $^{239}\text{Pu}$ ,  $^{240}\text{Pu}$ ,  $^{241}\text{Pu}$ , and  $^{242}\text{Pu}$ ).

The chosen excitation schemes rely on strong optical dipole transitions, which are constrained by the corresponding selection rules. For a total angular momentum of  $J = 0$  in the atomic ground state, the specific laser polarizations affect the measured isotope ratios and must be considered, e.g., in the case of even mass plutonium isotopes. Exploiting this dependence opens up an additional path to discriminate even-even isotopes against interfering background.[4] This approach was demonstrated on samples of  $^{239-242}\text{Pu}$  isotopes.

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## Isotope Separation of 53-Manganese by Resonance Ionization Mass Spectrometry

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In the framework of the MeaNCORN-Project (Measurement of Neutron capture cross sections and determination of half-lives of short-lived Cosmogenic Radio-Nuclides) [1] of the Paul-Scherrer-Institut (PSI), ultrapure samples of the long-lived radioisotope  $^{53}\text{Mn}$  ( $t_{1/2} = 3.7$  Ma) are needed to precisely determine its lifetime and neutron capture cross section. For this task,  $\mu\text{g}$  quantities (corresponding to about  $10^{17}$  atoms) of the isotope, need to be implanted into Al targets with highest possible isotope purity and minimum loss, i.e. highest efficiency, by suppressing the more frequent short-lived and stable isotopes  $^{54,55}\text{Mn}$ .

The highly efficient and selective technique of resonance ionisation mass spectrometry (RIMS) has been adapted to Mn at the Mainz RISIKO mass separator and optimized to provide efficient isotope separation also at comparably high ion beam currents in the region of up to  $1\ \mu\text{A}$ . Reaching typical overall implantation efficiencies around 15 %, the requested sample size could be provided with sufficient purity. The efficient minimum loss sample purification can support accelerator mass spectrometry (AMS) applications on  $^{53}\text{Mn}$  by suppressing neighbouring isotopes for background reduction. On top of that, an additional isobar suppression, e.g. against  $^{53}\text{Cr}$ , needs to be foreseen for AMS to achieve required extremely high selectivity of Mn isotopes in the range of  $10^{16}$ .

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## RFQ ion guides for In-Gas Laser Ionisation and Spectroscopy experiments

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The In-Gas Laser Ionization and Spectroscopy (IGLIS) techniques enables medium-resolution laser spectroscopy on radioactive ion beams stopped in a gas cell[1,2]. The in-gas jet method overcomes the typical broadening effects present in a gas cell or hot cavity ion source by performing laser ionization in the homogeneous cold and low-density supersonic gas jet produced by a contoured nozzle installed at the gas cell exit [3].

The offline IGLIS setup at KU Leuven utilizes a set of three different radiofrequency ion guides to efficiently transport resonantly ionized isotopes from the jet towards the mass separation and the subsequent detection. The RFQ ion guides are commissioned with ion beams from stable isotopes and have been characterized with respect to transport efficiency, transient time, energy dispersion and transverse emittance of the extracted ion beam. Ion-trajectory and flow dynamics simulation with different ion-neutral interaction potentials have been performed in order to understand the cooling and are compared to the reported experimental results.

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## Absolute frequencies of the $5s^2\ ^1S_0 \rightarrow 5s5p\ ^3P_1$ hyperfine transitions in $^{115}\text{In}^+$ using collinear laser spectroscopy

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Collinear laser spectroscopy has been used for more than 30 years to study nuclear properties like spins and moments or the change in the mean-square charge radius deduced from the isotope shift. Typically, isotope-shift measurements are done relative to a reference isotope due to the large uncertainty in the determination of the acceleration voltage of the ions that interact with the laser. For charge radii measurements of very light ions a method was developed that eliminates the unknown voltage from the frequency calculation by combining the results from a collinear and an anti-collinear laser interaction using two independent laser systems and the precise frequency measurement with an optical frequency comb [1]. With this method the extraction of absolute transition frequencies became possible with unprecedented precision in collinear laser spectroscopy.

At TU Darmstadt we have set up an off-line collinear laser spectroscopy setup (COALA) where we applied this technique for absolute frequency measurements of the hyperfine structure in the  $5s^2\ ^1S_0 \rightarrow 5s5p\ ^3P_1$  intercombination transition of stable  $^{115}\text{In}^+$  emitted from a liquid metal ion source. Our measurement of the  $F=9/2 \rightarrow F=11/2$  is in excellent agreement with a trap measurement [2] and we were able to improve the uncertainties of the  $F=9/2 \rightarrow F=9/2$  and the  $F=9/2 \rightarrow F=7/2$  by nearly two orders of magnitude compared to literature values [3]. With these measurements we were able to also deduce improved values for the hyperfine splitting A and B factors.

We will present the experimental technique and show the results from the absolute-frequency measurements.

This work was supported by BMBF under contract 05P19RDFN1 and by DFG under contract SFB1245.

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## High-Voltage Metrology via Collinear Laser Spectroscopy

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Many precision experiments, e.g. at storage rings or KATRIN, rely on accurate high-voltage measurements. These are usually carried out with high-voltage dividers which are limited to an accuracy

of up to 1 ppm ( $k=1$  standard uncertainty) due to an intricate, step-wise calibration tracing back to low-voltage Josephson standards. The susceptibility of the resistors to thermal changes and aging effects is the main source of systematic uncertainties and prohibits a long-term stability leading to limitations of high-precision experiments.

We report on a laser spectroscopic approach for a direct high-voltage evaluation which has been set up at TU Darmstadt and is capable to overcome the 1 ppm threshold set by the conventional technique. Using a two-chamber pump-and-probe scheme, accuracies in the ppm regime have been already demonstrated [1]. Further improvements in the experimental setup such as laser-ion-beam superposition and laser-frequency stabilization by a frequency comb have been successfully realized to reduce the remaining uncertainties. The corresponding techniques as well as the latest results will be presented.

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## Novel ways in studying the atomic structure of superheavy elements

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The discovery of superheavy elements (SHEs) has created new facets of chemical and physical exploration, not only in a theoretical framework, but also under extreme experimental conditions. A fascinating aspect concerns the atomic structure of these elements. With increasing atomic number, relativistic effects increasingly influence the electron binding energies. Hence, deviations from the periodicity that is imprinted in the periodic table start to emerge such that simple extrapolation of systematics along the chemical homologues may not lead to reliable predictions anymore. In addition, the interaction between the electrons in the atomic shells can only be treated by certain approximations in modern atomic modeling with limited precision.

Experimentally, the “classical” way of optical spectroscopy utilizing primed discharge tubes in combination with spectrographs requires having at least weighable samples, which cannot be obtained for SHEs with current production technologies. These elements are synthesized solely in single-atom-at-a-time quantities what made their atomic structure investigations lagging behind. To study these heavy elements, new and novel multidisciplinary approaches with extreme sensitivity must be developed [1,2]. A great leap forward in this field was recently achieved with the successful laser spectroscopy of the element nobelium ( $Z=102$ ) despite a complete lack of tabulated spectral lines, short half-lives, and production rates on the order of one atom per second [3,4,5].

In my talk, I will give a survey on laser spectroscopy techniques that are being developed for atomic structure investigations in the region of the heaviest elements, present recent results, and focus on the prospects for studying SHEs. In the same context, I will introduce ion mobility spectrometry and explain how it can help elucidating an element’s electronic configuration [6].

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## On-line resonant ionization laser ion source operation –quo vadis?

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Resonance ionization laser ion sources (RILIS) are being implemented and used as part of the ion source inventory of modern radioactive ion beam facilities. As a significant number of elements are now accessible with highly efficient laser ionization schemes the nature of RILIS operation at on-line facilities is changing and moving from beams at highest intensities towards beams of e.g. increased purity, isobar selectivity, versatility and operational reliability.

The trends observed and developments undertaken at TRIUMF's on-line RILIS operation will be shown and discussed.

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## Towards day one experiments at the S3 Low-Energy Branch

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Resonant Laser Ionization and Spectroscopy are nowadays powerful techniques to produce pure low energy beams of exotic nuclei and to provide valuable information on their atomic and nuclear ground state properties. The S3 Low Energy Branch (S3 LEB), the new state of the art apparatus based on the 'In-Gas Laser Ionization and Spectroscopy' (IGLIS) technique [1], will benefit from the

very exotic beams produced by fusion evaporation reactions, by the high selectivity and high transmission S3 Super Separator Spectrometer [2] currently under construction at SPIRAL2/GANIL. The first experimental campaigns using the S3LEB set-up will focus on medium-mass nuclides along the  $N = Z$  line from  $Z = 40$  (Zr) to  $Z = 56$  (Ba), including the doubly magic  $^{100}\text{Sn}$ , the heavy actinide region (Ac and U) and the super heavy element region (around No  $Z=102$ ). Based on this program, a list of elements has been chosen for the “day one” experiments considering the potential physics output and the different aspects of the instrument that will be commissioned.

In this contribution, we will present, for each “day one” element, the different S3LEB set-up configurations that have to be prepared, as, for example, the gas-cell configuration and the atomic spectroscopy and ionization schemes that have to be provided by the TiSa laser system available for the first years of experiments. These results will trigger a discussion on the technical choice for the narrow bandwidth laser needed for the medium high-resolution spectroscopy of these elements.

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## A cryogenic linear Paul trap for the Multi Ion Reflection Apparatus for Collinear Laser Spectroscopy

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Collinear laser spectroscopy (CLS) is a powerful tool to access nuclear ground state properties of short-lived radionuclides [1,2]. However, in order to explore the most exotic nuclides with very low production yields at radioactive ion beam (RIB) facilities, more sensitive methods have to be envisioned. Complementary to the Collinear Resonance Ionization Spectroscopy technique (CRIS) [3], the novel MIRACLS project at ISOLDE/CERN, aims to combine the high spectral resolution of conventional fluorescence-based CLS with high experimental sensitivity. This is achieved by trapping ion bunches in a novel 30 keV MR-ToF (Multi-Reflection Time of Flight) device [4], in which the ions bounce back and forth between two electrostatic mirrors such that the laser-ion interaction time is increased with each revolution.

The combination of CLS and MR-ToF techniques in MIRACLS constitutes stringent requirements on the emittance of the probed ion bunches. A low energy spread ( $< 1$  eV) to minimize the CLS Doppler broadening is as essential as a temporally narrow ion-bunch profile ( $< 500$  ns) for MR-ToF operation. Moreover, the transversal emittance should be as small as possible to maintain ion trajectories parallel to the laser-beam axis over thousands of revolutions inside the MR-ToF device.

Although specialised linear Paul traps have explored the benefits of cryogenic environments cooled by LN<sub>2</sub> [5], conventional devices for beam cooling and bunching at RIB facilities operate at room temperature. As the emittance scales linearly with the “buffer gas temperature” [16], a compact, linear Paul trap with cryogenic cooling down to  $< 40$  K is currently designed, to meet the emittance requirements at MIRACLS.

This trap will be separated into two pressure regions, a high pressure region for ion stopping and cooling followed by a low pressure region for extraction. The latter is crucial to minimize collisions of ions with buffer gas atoms along their extraction and reacceleration path, which would otherwise lead to an undesired “reheating” of the cold ion ensemble.

This poster will briefly introduce the MIRACLS concept and present the simulation and design status of a compact, cryogenic cooled, linear Paul trap for optimal beam preparation.

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## Determination of the electron affinity of astatine

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Astatine, element 85, is the rarest naturally occurring element in earth's crust. It only exhibits a number of short lived alpha emitting isotopes produced as a daughter from various decay chains. One of the longer lived isotopes, <sup>211</sup>At, is of special interest as an agent for targeted alpha therapy (TAT), a method of treating cancer directly at the location of a tumor with alpha emitting particles. Due to its short life-time and scarcity, some fundamental properties of astatine such as the electron affinity (EA), are not yet known. The electron affinity combined with the previously measured ionization potential (IP) determines the electronegativity which serve as valuable benchmark for quantum chemical calculations predicting the chemical properties of this element and its compounds. The Gothenburg Anion Detector for Affinity measurements by Laser PHotodetachment (GANDALPH) was designed for the determination of the EA of radioisotopes produced at ISOLDE. Following the first measurement of the EA of radiogenic <sup>128</sup>I in 2016, GANDALPH has recently received multiple upgrades to facilitate beam tuning and detection of low intensity ( $< 1$  pA) ion beams. During an experimental campaign at CERN-ISOLDE in 2018, the GANDALPH setup was used to successfully measure the EA of astatine. Experiment and results of these measurements will be presented and compared to expectations and recent theoretical calculations.

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## TRIUMF off-line laser ion source development

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Resonance ionization laser ion sources (RILIS), providing element selective ionization, has been used worldwide at various accelerator facilities to deliver isobar-suppressed radioactive beams to nuclear physics, astrophysics and condense matter experiments.

To develop optimal laser ionization schemes, especially those via highly efficient autoionizing (AI) states, an off-line laser ion source test stand (LIS-STAND) with an adjacent laser laboratory was added to the on-line facility in 2008. Since then a variety of elements have been studied by laser resonance ionization spectroscopy at the LIS-STAND. A number of efficient ionization schemes have been developed and were successfully applied to on-line radioactive ion beam delivery. An update on recent off-line developments will be presented. This includes laser development, temperature and polarization dependence investigations of the RILIS efficiency and the latest laser spectroscopy results in search of Rydberg and AI states.

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## Search for CP violation in nuclear beta decays: the MORA project

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Why are we living in a world of matter? What is the reason for the matter–antimatter strong asymmetry observed in the Universe? The MORA (Matter’s Origin from the RadioActivity of trapped and oriented ions) project aims at searching for possible hints in nuclear beta decays, through the measurement of correlations sensitive to CP violation. Such a violation is expected to be a fulfilled primary condition in the baryogenesis process and it is already implemented in the Standard Model

via the quark-mixing mechanism, but at a level which is not sufficient to account for the large observed matter-antimatter asymmetry. A large window remains unexplored today, from which a New Physics (NP) can potentially emerge.

The goal of MORA is the measurement of the triple correlation parameter  $D$  in mirror decays with relevant precision. This requires the use of a detection setup sensitive to the angular correlation between the two leptons emitted by oriented radioactive nuclei. The main device of MORA is thus an optimized LPCTrap-like transparent Paul trap surrounded by a detectors crown enabling the measurement of the coincidences between the beta particles and the recoil ions coming from the confined radioactive source. The total angular momenta of the decaying nuclei will be oriented using polarized pulsed lasers, which should provide a very high degree of polarization in a reasonable time. Such a process has never been achieved so far in a 3D Paul trap. The parameter  $D$  will be deduced from an asymmetry observed in the counting rates when inverting the polarization direction. The setup will be first installed at JYFL where adequate lasers exist for  $^{23}\text{Mg}^+$  ions. This interesting candidate can be produced at the IGISOL facility with a sufficient rate to start the project. At a precision level of  $10^{-5}$ , the measurement should enable for the first time a probe of the Final State Interaction effect which mimics a non-zero  $D$  correlation. MORA will be later installed in the DESIR hall at GANIL where higher production rates are expected, giving the opportunity to reach unprecedented sensitivity to NP.

The current status of the project and perspectives will be presented at the conference.

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## Development of quartz resonators for Fourier transform ion cyclotron resonance mass spectrometry on single super heavy ions

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Fourier transform ion cyclotron resonance (FTICR) has been the cutting edge technique of mass spectrometry of single ions in the recent years. Several experiments have shown outstanding performances pushing the border of precision beyond  $10^{-10}$  for a single ion of selected stable nuclides. All experimental setups made use of specially designed and manufactured superconducting coils to form a LC tank circuit with the capacity of the Penning trap electrode connected to it to reach single ions sensitivity. As a mandatory experimental constrain it is necessary to cool the setup with liquid Helium to achieve superconductivity. Due to limited space and cooling capacity in the experimental setup of TRIGA TRAP, superconducting coils can not be used. Quartz resonators with specially cut quartzes were designed and produced to match the experimental needs of high  $Q$  value and compact dimensions allowing an installation near the trap centre. Super-heavy ions are especially challenging to investigate with this technique due to their low cyclotron frequencies, typically  $< 1$  MHz, low charge state, typically doubly charged, and rather short half-lives. A novel amplifier was designed specifically adapted to the quartz application providing an outstanding performance with high  $Q$  value and very low electrical noise levels. An overview of the current status is given and first designs of the quartzes and amplifier are presented. Furthermore, first measurements with ion clouds are presented demonstrating the feasibility of the concept.

## Mass measurements of neutron-deficient lanthanides around the neutron shell closure N=82

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Neutron-deficient lanthanides are a subject of interest from many perspectives. Not only can they provide information about the neutron shell closure at N=82, but they can also indicate where the proton drip-line lies in this region. In addition, since some lanthanides are anchors of alpha decay chains, they can give valuable information about the progenitors and intermediate nuclei.

To this end, the masses of neutron-deficient lanthanides, approaching the atomic number 150, were measured at TRIUMF's Ion Trap for Atomic and Nuclear science (TITAN). TITAN specializes in high-precision mass measurements and in-trap decay spectroscopy, which recently was equipped with a Multi-Reflection Time of Flight mass spectrometer (TITAN MR-ToF) that can be used either as an isobaric separator or a mass spectrometer. For this experiment, radioactive ion beam from the TRIUMF's Isotope Separator and Accelerator (ISAC) was used to trap and measure neutron deficient lanthanides in TITAN's Multi-Reflection Time of Flight mass spectrometer. Mass-selective re-trapping was used for the first time with radioactive beam and resulted in suppression of the background by four orders of magnitude. This allowed the measurement of the masses of neutron-deficient lanthanides, Yb and Tm. Not only were many uncertainties reduced but also some measured for the first time. The impact of these mass measurements to the evolution of the neutron shell closure at N=82 will be discussed.

## Charge Radii of Boron Isotopes

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We report on the first laser spectroscopic determination of the nuclear charge radius of stable boron isotopes by resonance ionization mass spectrometry (RIMS) [1].

Boron atoms generated from a thermal source were ionized using two laser systems. A frequency-quadrupled continuous-wave Ti:Sa laser was scanned across the atomic ground-state resonance at about 250nm. A high-power frequency-doubled continuous-wave Nd:YAG laser was used to ionize the previously excited atoms. Using a quadrupole mass spectrometer and a single-ion detector, the generated ions were detected, and the hyperfine structure was recorded almost background-free. An elaborate laser spectroscopic setup, using perpendicular overlap between laser and atomic beam, allowed to correct for residual Doppler-shifts with high accuracy. A frequency comb was employed to remove various systematic uncertainties that usually have to be considered with this type of measurement. The isotope shift between the two stable isotopes  $^{10,11}\text{B}$  was extracted with an uncertainty of the order of 1 MHz.

Although atomic theory is not yet able to extract absolute transition energies for something more complicated than a one-electron-system, it is possible to calculate the mass-dependent isotope shift with spectroscopic accuracy since all mass-independent contributions and their related uncertainties cancel. This atomic QED calculation was done and employed here for the first time for a five-electron system. We then combine the results of our high-resolution measurement of the isotope shift with the novel high-accuracy *ab initio* mass-shift calculations. The remainder between the calculation and experiment is called the field shift and is attributed to the nuclear volume effect. From this, we were able to extract the difference in the mean-square charge radius between the stable isotopes  $^{10,11}\text{B}$ .

This result is then used to benchmark new *ab initio* nuclear structure calculations using the no-core shell model and Green's-Function Monte Carlo approaches. The results present a striking convergence of these nuclear calculations, atomic theory and experiment combined on a high precision level. Furthermore, they are a showcase for further precision spectroscopy experiments to come at the limits of nuclear stability.

In near future, collinear laser spectroscopy will be performed in the same transition on the short-lived (770ms) proton halo candidate  $^8\text{B}$  at Argonne National Laboratory. The difference in mean-square charge radius will deliver a model-independent test of its proton halo character. The contribution will also highlight the status and perspectives of this ongoing experimental work.

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## The Spectrum of Antihydrogen

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According to the CPT (Charge, Parity, Time) theorem the spectrum of hydrogen must be identical to that of its counterpart antihydrogen, the bound state of an antiproton and a positron. However, the universe is highly asymmetric to such an extent that apparently no bulk antimatter exists. This conundrum could be due to a small yet unobserved difference between matter and antimatter, wherefore a range of experiments pursue precision comparisons of the two. In particular the comparison of matter and antimatter atoms holds the promise of the highest precision. The ALPHA experiment has since 2010 been able to synthesize, trap and hold antihydrogen atoms in a magnetic trap, and observed the first atomic transition, a positron spin flip in the ground state, in 2012 with a total of 300 antiatoms for the experiment.

An upgrade of the apparatus and subsequent advances in trapping efficiencies and access, means that we can now work with samples of 1000's of antihydrogen atoms . This boost has aided in a recent string of successes in observing a number of optical transitions in antihydrogen. The most prominent result to date being the probing of the 1S-2S transition to a precision of  $2 \times 10^{-12}$ . The result of this most precise and accurate measurement on antimatter to date was in agreement with the value expected for hydrogen in similar experimental conditions, and thus constituted a stringent test of CPT. We have also explored the 1S-2P transition using pulsed laser-light with the goal of laser-cooling the antihydrogen atoms and thereby assist in increasing the precision of the 1S-2S and other measurements . Finally we have further probed the hyperfine levels of the ground state and measured the hyperfine splitting to a precision of  $4 \times 10^{-4}$  .

In this presentation we'll report on what went in to achieving these successes, and on how we plan to push the limit further to become competitive with measurements on normal matter, and eventually compare matter and antimatter to even higher precision.

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## Status and perspectives of the S3 Low-Energy Branch at SPIRAL2-GANIL

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Laser and decay spectroscopy together with mass spectrometry lay the foundation of nuclear-structure studies and are key to the exploration of new regions of the nuclear chart. The Low-Energy-Branch (LEB) experiment that will be installed at the final focal plane of the Super Separator Spectrometer (S3) at SPIRAL2 [1] will bring together cutting-edge techniques of all three fields in order to study very neutron-deficient nuclides close to the  $N = Z$  line and heavy actinides, both of which are very poorly known experimentally. The In-Gas Laser Ionization and Spectroscopy (IGLIS) in a supersonic gas jet, which is at the core of the installation, will greatly improve the spectral resolution of

hyperfine-structure studies [2, 3]. This in turn is crucial for the determination of nuclear moments and spin, as well as for achieving isomer selectivity.

This contribution will present the status of the S3-LEB experiment, currently being assembled and tested off-line at LPC Caen and GANIL. Results of the tests being performed at LPC and at the off-line IGLIS laboratory in KU Leuven [4] will be presented, together with an update of the technical and physics goals of the project and of the commissioning program.

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S3 has been funded by the French Research Ministry, National Research Agency (ANR), through the EQUIPEX (EQUIPMENT of EXcellence) reference ANR-10EQPX- 46, the FEDER (Fonds Européen de Développement Economique et Régional), the CPER (Contrat Plan Etat Région), and supported by the U.S. Department of Energy, Office of Nuclear Physics, under contract No. DE-AC02-06CH11357 and by the E.C.FP7-INFRASTRUCTURES 2007, SPIRAL2 Preparatory Phase, Grant agreement No.: 212692.

S3 LEB has been funded by the French Re-search Ministry through the ANR-13-B505- 0013, and the Flemish Research Fund (FWO) under the Big science program and a grant from the European Research Council (ERC-2011-AdG-291561-HELIOS).

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## Laser Cooling and Trapping of Cs Isotopes and Isomers: Progress and Perspectives

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We will report on the design, installation and test of an experimental facility for the production of ultra-cold atomic Cs isotopes and isomers. The facility is installed at the Accelerator Laboratory of the University of Jyväskylä (Finland), and it was realised by a collaboration of University College London, University of Jyväskylä, and University of Surrey [[1]]. The desired  $^{A,Am}\text{Cs}^+$  species is produced by proton-induced fission or fusion-evaporation in the IGISOL-4 facility [[2]]. Ions are then mass-separated, routed to the experimental chamber, and neutralised by thin-foil implantation. A thermal vapour of neutral  $^{A,Am}\text{Cs}$  atoms is then laser cooled and trapped in a magneto optical trap. Atomic samples of density  $10^{10} \text{ cm}^{-3}$  at  $150 \mu\text{K}$  are obtained.  $^{A,Am}\text{Cs}$  are brought from  $10^4 \text{ eV}$  to  $10^{-8} \text{ eV}$  in around 5 s, at full capacity.

The availability of cold and dense atomic samples of Cs isotopes and isomers opens new avenues for high-precision measurements of isotopic and isomeric shifts, thereby gaining deeper insight into the nuclear structure. In particular, direct comparison of optical transitions shifts in  $^A\text{Cs}/^{Am}\text{Cs}$  pairs provides novel data for investigating the charge radii variations and the nuclear shape. Highly-selective trapping and detection of small traces of given Cs isotopes allow for sensitive measurements of isotopes' concentration ratios in trace quantities for nuclear forensics, environmental control, and security. Finally, we will also discuss the perspectives for the realisation of an isomeric Bose-Einstein condensate, and of the long-awaited experimental demonstration of coherent gamma photons generation [[3]].

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#### ACKNOWLEDGMENTS

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## Laser spectroscopy of BaF for an eEDM measurement

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The observation of a CP-violating electron electric dipole moment (eEDM) larger than the value predicted by the Standard Model (SM) of particle physics would be direct evidence of New Physics. An upper limit of the eEDM constrains extensions to the SM. The structure of molecules such as barium monofluoride (BaF) induces a strong enhancement of the CP-violating effects. We are in the process of building an experiment to attain a new upper limit for the value of the eEDM using BaF<sup>1</sup>.

BaF is an excellent system for eEDM searches because its structure allows for Stark deceleration and efficient laser cooling. In order to exploit the intrinsic sensitivity of BaF for eEDM measurements, laser spectroscopy is an essential tool, e.g.: state manipulation, state-sensitive optical detection, polarisation, and laser cooling. We will discuss the laser parameters required for the multiple laser applications in our experiment. In addition, we will present laser spectroscopy of an intense BaF beam from a supersonic source, extracting indispensable parameters of the system for the final eEDM measurement.

<sup>1</sup> The NL-eEDM collaboration, Aggarwal, P., et al. Eur. Phys. J. D (2018) 72: 197. <https://doi.org/10.1140/epjd/e2018-90192-9> and references therein.

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## Charge radii of neutron-deficient Ca isotopes

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The chain of charge radii,  $\langle r_2 \rangle$ , of Ca isotopes has been challenging nuclear theories to reproduce its peculiar behavior: the similar  $\langle r_2 \rangle$  of  $^{40}\text{Ca}$  and  $^{48}\text{Ca}$  despite eight neutrons added, and the strong odd-even staggering in between 1. Recent observations of unexpectedly large  $\langle r_2 \rangle$  of neutron-rich Ca isotopes 2 shows the necessity of a more advanced approach to model the chain of Ca  $\langle r_2 \rangle$ .

The  $\langle r_2 \rangle$  of neutron-deficient  $^{36,37,38}\text{Ca}$  isotopes were determined 3 for the first time in the present study at the BEam COoling and LAsEr spectroscopy (BECOLA) facility [4] at NSCL/MSU. The collinear laser spectroscopy technique [4] was used to measure atomic hyperfine spectra, from which  $\langle r_2 \rangle$  were deduced.

The density functional theory (DFT) with Skyrme or Fayans energy density functional strongly overestimates present  $\langle r_2 \rangle$  of  $^{36,37,38}\text{Ca}$ . It was found that the weak binding effect of protons in these neutron-deficient Ca isotopes results in this discrepancy. The improved model with a coupling to the proton continuum successfully reproduces  $\langle r_2 \rangle$  of not only the neutron-deficient Ca isotopes but also the entire intricate pattern of the chain of Ca  $\langle r_2 \rangle$  all the way to  $^{52}\text{Ca}$ .

The detail of the experiment and the interpretation of data with the DFT will be discussed.

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## Towards Laser Spectroscopy of $\text{Mg}^{+}$ at CRYRING@ESR for Optical Pumping Studies and Laser Velocimetry

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CRYRING@ESR is a low-energy storage ring integrated in the GSI accelerator facility and the Swedish contribution to the FAIR project. Both, highly-charged ions from the Experimental Storage Ring (ESR) as well as singly-charged ions created by a standalone Penning ion source can be injected into the ring. The latter produces  $^{24}\text{Mg}^{+}$  ions for the envisaged laser spectroscopy experiment. This will take place in one of the straight sections of CRYRING@ESR where laser and ion beam will be



aligned. A mirror chamber manufactured by the group of Prof. Weinheimer in Münster is mounted in the vacuum for photon collection. Fluorescence photons are guided to PMT's mounted on windows outside the vacuum. The newly installed FPGA-based Data Acquisition System TILDA is used for single photon tagging and enables time-resolved spectra with a time resolution of 10ns.

For both optical pumping studies as well as laser velocimetry of high voltages  $^{24}\text{Mg}^+$  is a suitable candidate. The D1 transition in  $^{24}\text{Mg}^+$  can be driven by circular polarized  $\sigma^+$ -light thus pumping the ground-state population to the substate with the highest magnetic quantum number. Due to preservation of angular momentum there is no excited state which can be addressed from this state by irradiation with  $\sigma^+$ -light. This will lead to a polarization of the electron shell and will be observable by a vanishing fluorescence signal. However, it is questionable whether the established polarization of the electron shell can be maintained during the rapid passage of magnetic fields along the ring. If successful - the same polarization scheme can be used for elements with hyperfine structure, creating a nuclear polarization. Investigations on parity violating processes would be possible with this method.

In previous beam times at the ESR the uncertainty of the electron cooler voltage determination was identified to be crucial for high precision measurements. At the moment voltage dividers achieve the highest accuracy in this matter. However, they are limited to a relative accuracy of 1 ppm. Another approach to measure high voltages is laser velocimetry where the optical Doppler Shift of a known transition frequency in ions or atoms is used to determine the high voltage applied for acceleration. This was successfully demonstrated on the level of a few ppm in the ALIVE project at TU Darmstadt [Krämer *et al.*, Metrologia 55, 268 (2018)]. In a second part of the upcoming experiment, we want to evaluate the velocity of the stored ions by laser velocimetry and compare it to the high-voltage at the CRYRING electron cooler measured with a new high-precision voltage divider built at University of Münster. The goal is to study to which extent the ion velocity might deviate from the calculated value based on the high-voltage due to systematic influences, like space charges or contact potentials.

We report on the present status of these experiments.

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## A New Experiment for the Measurement of the Magnetic Moments of $^3\text{He}^{2+}$ and $^3\text{He}^+$

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We are setting up a new experiment dedicated to the measurement of the electronic and nuclear magnetic moments of  $^3\text{He}^{2+}$  ( $\mu_{He}$ ) and  $^3\text{He}^+$ . The project aims at the first direct measurement of  $\mu_{He}$  with a relative precision of  $10^{-9}$  or better and an improvement of the ground-state hyperfine splitting in  $^3\text{He}^+$  with a precision at the 10 ppt level.

The measurement of the ground-state hyperfine splitting in  $^3\text{He}^+$  will complement the determination of nuclear structure effects in  $^3\text{He}$  as pursued in more sensitive but less precise experiments on muonic systems. Furthermore the measurement of  $\mu_{He}$  will establish hyper-polarized  $^3\text{He}$  as an independent magnetometer, which exhibits smallest systematic corrections concerning sample shape, impurities and environmental dependencies but lacks an independent and direct measurement of  $\mu_{He}$ . Once  $\mu_{He}$  is measured in this experiment, hyper-polarized  $^3\text{He}$  can serve as an uncorrelated magnetic field probe with the potential to second challenging absolute magnetic field measurements as e.g. in the case of the g-2 measurement of the muon. In addition, a complementary determination of the anomalous magnetic moment of the muon becomes possible.

To date, Penning traps are the tool of choice for direct high-precision measurements of nuclear magnetic moments. The employed methods rely on the detection of single spin flips whose detection fidelity is however limited by the mode-energies of the trapped ions [A. Mooser *et al.*, Phys. Rev.

Lett. **110**, 140405 (2013)]. If applied to  $\mu_{He}$ , the methods would hinge upon an insufficient detection fidelity. Thus, the experiment aims to decrease the mode-energies by more than two orders of magnitude compared to classical approaches. This will be achieved by applying sympathetic laser cooling, coupling a single  $^3He$  ion to a reservoir of laser-cooled beryllium ions in a neighboring Penning trap [M. Bohmann *et al.*, J. Mod. Opt. **65**, 568 (2017)].

In the contribution developments towards sympathetic laser cooling, magnetic moment measurements and prospects of an absolute magnetic field probe using hyper-polarized  $^3He$  will be presented.

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## Production of clean rare isotope beams at TRIUMF's Isotope Separator & Accelerator Facility

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Hot cavity resonant ionization laser ion sources (RILIS) provide a multitude of radioactive ion beams to users. High ionization efficiency and element selective ionization characterize resonant ionization laser ion sources RILIS. At ISOL facilities RILIS usually are of the hot cavity type, where laser ionization takes place inside a hot cavity. Therefore, isobaric contamination from surface ionized species remains and reduces the purity of the extracted beam.

In order to overcome this, an ion guide-laser ion source (IG-LIS) has been developed in which the hot isotope production region is separated from the laser ionization volume. A number of on-line experiments with beam delivery have been conducted at ISAC. Isobar suppression of up to  $10^6$  has been achieved at the cost of an overall intensity loss of 50-100x as compared to hot cavity RILIS.

Operating parameters for IG-LIS are being optimized and design improvements are being implemented for a more robust and higher efficiency on-line operation. Recent SIMION simulation results and the current, ongoing development status of our ion-guide laser ion source will be presented.

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## Binding energy studies at the extreme of the nuclear landscape with ISOLTRAP

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Binding energies are among the first observables reaching in yet uncharted regions of the nuclear chart and their trends are sensitive to a wide range of nuclear-structure phenomena. As such, they provide invaluable inputs to all nuclear models.

Over the last years the ISOLTRAP high-precision mass spectrometer [1-2], located at ISOLDE/CERN, was intensively used to probe the region around  $N=82$  below the tin isotopic chain. More specifically, the strength of the  $N=82$  shell closure in neutron-rich Cd isotopes near  $^{130}\text{Cd}$  and its implications on the r-process nucleosynthesis has already been studied [3]. Recent results from an extension of this campaign to Cd isotopes beyond  $N=82$  will be presented. Additionally, several odd-even Cd isotopes below  $N=82$  were shown to exhibit long-lived isomeric states [4]. Conventional Penning-trap mass spectrometry techniques had already provided direct measurements of the excitation energies of  $^{125m,127m}\text{Cd}$  [5] but the energy of the elusive  $^{129m}\text{Cd}$  state has yet to be measured. The successfully commissioned phase-imaging ion-cyclotron-resonance technique [6] now completes ISOLTRAP's arsenal of high-resolving power and high-sensitivity mass spectrometry techniques thus enabling for isomeric separation within a few hundred milliseconds. Thus, recent results from the application of this technique for  $^{127}\text{Cd}$  and  $^{129}\text{Cd}$  will be presented.

On the opposite side of the nuclear chart, a mass measurement campaign was dedicated to the study of neutron-deficient In isotopes in the vicinity of the doubly-magic  $^{100}\text{Sn}$ . This campaign performed at the extreme of the nuclear landscape was successful and the mass measurement of  $^{99-101}\text{In}$  allowed us the investigation of the  $Z=N=50$  shell closure in close proximity with the proton drip-line. This contribution will also present results from this campaign.

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## Advances in the Search for the Electric Dipole Moment of Radium-225

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Permanent electric dipole moments (EDMs) are signatures of time-reversal, parity, and charge-parity (CP) violation, which makes them a sensitive probe of physics beyond the Standard Model (BSM), such as supersymmetry. Due to its large nuclear octupole deformation and high atomic mass, the radioactive Radium-225 isotope (14.9 days half-life) is a favorable EDM case; it is particularly sensitive to CP-violating interactions in the nucleus. To probe this rare species, we have developed a unique cold-atom approach, where laser-cooled radium atoms are suspended in an optical dipole trap. This enables us to leverage the small number of atoms available with long trap lifetimes, high electric fields, and sensitive state detection. Using this method, we have found the EDM of Ra-225 to be less than  $1.4 \times 10^{-23}$  e-cm (95% C.L.). New improvements are underway to dramatically enhance our sensitivity through efficiency increases in optical trapping and nuclear spin readout of the rare atoms. The status of these upgrades, along with potential impacts on BSM physics will be discussed. This work is supported by the U.S. DOE, Office of Science, Office of Nuclear Physics, under contract DE-AC02-06CH11357.

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## Single atom heat engine with quantum load

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Ion trap technology is a forerunner in quantum computing, simulation, sensing and clocks. The versatile application of ion trap setups stem from their ability to control and manipulate single or multiple ions in a near isolated environment with negligible kinetic energy. Two such applications related to fundamental physics 1 and thermodynamics 2 at the quantum scale have been recently demonstrated in our setup. These two applications will be discussed in detail. In the first application we demonstrate that by proper feedback or noise filtering it is possible to preform frequency measurement with precision beyond the Heisenberg limit. The second experiment deals with understanding thermodynamics at the quantum limit. Both the experiments have been carried out using barium ion in a linear Paul trap using protocols engineered for each tasks.

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## Trapped ion quantum information processor

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## Content

Quantum information processing including quantum computing has developed to a stage when it can be translated to real life application. Solving hard computational problems, securing communication, sensing etc. forms the basis of quantum technology landscape. Ion traps have emerged as a forerunner in the field of quantum computation. In recent times, both research laboratories as well as private companies have shown viable roadmaps to implement full scale quantum computers in an ion trap platform. Therefore, it is an opportune time to dive into the details of how such a quantum computer works.

In this tutorial, basics of ion trapping, laser cooling and quantum manipulation methods as applicable to ion trap quantum processor will be discussed. In addition, various gate implementations, error rates, mitigation procedures etc. will be worked out. As an outlook, we will compare ion trap processor with other viable alternatives.

Primary author(s) : Prof. MUKHERJEE, Manas (Centre for Quantum Technologies, National University of Singapore)

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Track Classification : Ion traps

Contribution Type : Invited talk

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## Influence of the current detection geometry at the COALA experiment on quantum interference in the hyperfine spectrum of $^{43}\text{Ca}^+$ ions

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At the COALA experiment at the TU Darmstadt high-precision collinear laser spectroscopy is used to determine isotope shifts of atomic transitions in singly charged ions. After acquiring atomic spectra experimentally, applying the right model to the data is of major importance in order to accurately extract atomic transition frequencies. If the distance between two spectral lines is of the order of the natural linewidth of the corresponding transition, quantum interference must be considered when analysing atomic spectra. The photon scattering rate then depends on the polarization of the incoming photon as well as on the final scattering angle. Therefore, exact information about the angular acceptance range of the detection system becomes essential. For the  $^{43}\text{Ca}^+$  ion this effect becomes measurable for the  $4s\ ^2S_{1/2} \rightarrow 4p\ ^2P_{3/2}$  transition which splits into six spectral lines due to its hyperfine structure.

We report on simulations of the angular acceptance range of our detection system at the COALA experiment and updates of measurements with  $^{43}\text{Ca}^+$  ions. The simulations were used to estimate the influence of quantum interference on the photon scattering rate of the  $4s\ ^2S_{1/2} \rightarrow 4p\ ^2P_{3/2}$  transition of  $^{43}\text{Ca}^+$ . For the calculation of the photon scattering rate, the Kramer-Heisenberg formula was used analogously to 1. Furthermore, we report on plans to modify our detection system to study this effect more closely.

**Acknowledgement** This work was supported by BMBF under contract 05P19RDFN1

1 R. C. Brown et al., Phys. Rev. A **87**, 032504 (2013)

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## Mass measurements of neutron-rich silver isotopes at JYFLTRAP with the PI-ICR technique

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The Phase-Imaging Ion-Cyclotron-Resonance (PI-ICR) technique, where the radial ion motion of an ion in a Penning trap is projected onto a position-sensitive detector 1, is now routinely used at the Penning-trap mass spectrometer JYFLTRAP 2. The method has a high enough resolving power to separate nuclear states with an energy difference of a few tens of keV for singly-charged ions with half-lives of several 100 ms. Mass measurements of neutron-rich silver isotopes have been performed at JYFLTRAP using the PI-ICR technique, allowing the separation of isomeric states in these nuclei. In addition to the mass measurements of the ground states, the excitation energies of the observed isomeric states were measured; some of them for the first time.

Investigation of neutron-rich silver isotopes is important both for nuclear structure and for astrophysics. Nuclear masses in this region provide information on the evolution of the Z=50 and N=82 shell closures, one- and two-neutron separation energies and pairing effects in the region. They are crucial for modeling the astrophysical rapid neutron capture process (r-process). Previous mass measurements of 112,114-124Ag at the ISOLTRAP Penning trap 3 using the ToF-ICR technique were hampered by the existence of low-lying isomeric states and difficulties to identify the measured state. In those studies 119Ag was not assigned as the ground state or isomer, and 121-124Ag were assumed to be an admixture of the states which increased the uncertainty of the measurements. In this contribution, I will discuss how the ground and isomeric states in neutron-rich silver isotopes were resolved and measured separately for the first time using the PI-ICR technique at JYFLTRAP.

1 S. Eliseev et al., Phys. Rev. Lett. **110**, 082501 (2013).

2 D.A. Nesterenko et al., Eur. Phys. J. A **54**, 154 (2018).

3 M. Breitenfeldt et al., Phys. Rev. C **81**, 034313 (2010).

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## A new gas-jet setup for laser spectroscopy of superheavy elements

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Experimental data on the hyperfine structure in superheavy elements (SHE) is important to obtain valuable information about their nuclear structure. In addition, the atomic properties of SHE are of special interest because they are difficult to predict by theoretical calculations due to complex relativistic effects. Therefore, a new gas-jet experiment is being developed, which aims to enable precise investigation of electronic states of rare atoms with the use of laser spectroscopy in a supersonic gas-jet. The study of SHE is realized by stopping fusion evaporation residues in a buffer gas cell after their production and separation at SHIP at GSI, Darmstadt. Subsequently, the fusion evaporation residues are transferred into a supersonic gas-jet, which is produced by a de Laval-nozzle. Laser spectroscopy in this jet enables a higher resolution compared to the previous RADRIS setup, resulting in spectral linewidths of few hundred MHz, granting access to valuable information on nuclear moments and spins which can be derived from the hyperfine structure and isotope shifts. This talk will summarize the current status of the experiment.

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## Determination of Nuclear Ground State Properties by Laser Spectroscopy

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The optical spectrum is a fingerprint of an atom and uniquely identifies it as a member of an element in the periodic table. Looking closely and with high resolution, we can observe small variations in the spectrum from isotope to isotope. These variations provide information about the atomic nucleus that has been exploited for more than a century to extract nuclear structure information. Spins, magnetic dipole and electric quadrupole moments can be obtained as well as changes in the mean-square nuclear charge radii. This tutorial will present experimental techniques that are applied to obtain spectra of short-lived isotopes, discuss how nuclear structure influences the atomic spectrum and how the observables are extracted, exemplified at some recent results.

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## Isotope shifts in $^{20,22}\text{Ne}$ - Precision measurements and global analysis

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We report new precision measurements of the  $^{22}\text{Ne}$ - $^{20}\text{Ne}$  isotope shift for several transitions, utilizing the method of dual-sideband spectroscopy 1, as well as state-of-the-art, ab initio field-shift calculations 2.

An immediate consequence of the new field shift factor is a substantial change to the previously determined charge radii of radioactive neon isotopes, including the two-proton halo candidate  $^{17}\text{Ne}$  3.

Our isotope shift results are combined with all other historical measurements (100 years, 50 publications, 230 transition shifts) in a global fit to obtain the isotope shifts of all fifty low-lying neon levels with high precision. These level shifts show a wealth of electronic, nuclear and relativistic phenomena.

Relying on the analogy between mass shift and fine-structure operators, we explain this plethora of neon level-shifts utilizing a small number of effective parameters in a global parametric investigation.

Our investigation provides a birds-eye view on the isotope shift phenomena neon, with consequences to other noble gasses. From this vantage point, we reinterpret every effort made to calculate neon mass-shifts *ab initio*, and show that a surprising agreement between experiment and theory is obtained.

1 Measurement of the  $^{20-22}\text{Ne}$   $3P_{2-3}D_{3-3}$  transition isotope shift using a single, phase modulated laser beam. Ben Ohayon, Gal Gumpel, Guy Ron

2 AMBiT: A program for high-precision relativistic atomic structure calculations. E. V. Kahl, J. C. Berengut

3 Charge radii of neon isotopes across the sd neutron shell  
K. Marinova, W. Geithner, M. Kowalska, K. Blaum, S. Kappertz, M. Keim, S. Kloos, G. Kotrotsios, P. Lievens, R. Neugart, H. Simon, and S. Wilbert.

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## The MARA low-energy branch

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The MARA low-energy branch (MARA-LEB) [1,2] is a novel facility currently under development at the University of Jyväskylä. Its main focus will be the study of ground-state properties of exotic proton-rich nuclei employing in-gas-cell and in-gas-jet resonance ionisation spectroscopy and mass measurements of nuclei close to the  $N=Z$  line of particular interest to the astrophysical rp process 3.

MARA-LEB will combine the MARA vacuum-mode mass separator [4] with a gas cell, an ion guide system and a dipole mass separator for stopping, thermalising and transporting reaction products to the experimental stations. The gas cell has been designed and built based on a concept developed at KU Leuven [5].

Following extraction from the cell the ions will be transferred by radiofrequency ion guides and accelerated towards a magnetic dipole for further mass separation before transportation to the experimental setups. Laser ionisation will be possible either in the gas cell or in the gas jet using a dedicated Ti:Sapphire laser system and will provide reliable experimental data on the ground-state properties of exotic isotopes close to the  $N=Z$  line.

Mass measurements will be achieved through a dedicated radiofrequency quadrupole cooler and buncher and a multiple-reflection time-of-flight mass spectrometer [6] which will be combined with



the facility. These devices will allow for mass measurements of several isotopes with high impact on the rp process and which could be used as test grounds for state-of-the-art nuclear models.

In this presentation we will give an update on the current state of the MARA-LEB facility.

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- 2 P. Papadakis et al., *AIP Conf. Proceed.* 2011, 070013 (2018).
- 3 R.K. Wallace and S.E. Woosley, *Astrophys. J. Suppl. Ser.* 45, 389 (1981).
- [4] J. Sarén, PhD thesis, University of Jyväskylä (2011).
- [5] Yu. Kudryavtsev et al., *Nucl. Instr. and Meth. B* 376, 345 (2016).
- [6] R.N. Wolf et al., *Nucl. Instr. and Meth. A* 686, 82 (2012).

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## Laser spectroscopy of neutron-deficient tin approaching 100Sn

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Collinear resonance laser ionization spectroscopy is a powerful technique which can provide a unique insight in nuclear properties such as spins, electromagnetic moments and changes in mean-square charge radii from near doppler-free measurement of the hyperfine structure of exotic isotopes. This technique was recently used at the collinear resonance ionization spectroscopy (CRIS) beamline at ISOLDE-CERN, for studying nuclear structure properties of neutron-deficient tin isotopes in the proximity of the heaviest self-conjugate doubly magic nucleus  $^{100}\text{Sn}$ . Understanding the nuclear structure evolution along the tin isotopic chain, approaching  $N=Z=50$ , has long been established as an important benchmark for testing nuclear many-body models [2,3,4].

Extensive offline testing using a recently commissioned ion source allowed the development of several previously unexplored laser ionization schemes of tin. The insight of their sensitivity to nuclear observables and overall efficiency laid foundation to the online study of the unstable nuclei.

The successful online experiment performed in August 2018 provided the first hyperfine spectra below  $^{108}\text{Sn}$  of ground and long-lived isomeric-states of the neutron-deficient tin isotopes, extending from  $^{124}\text{Sn}$  down to  $^{104}\text{Sn}$ . These new measurements allow the first ever determination of electromagnetic moments, changes in mean-square charge radii and ground-state spin assignment of  $^{104-107}\text{Sn}$ , shedding a new light on the level ordering and collectivity approaching  $^{100}\text{Sn}$ .

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- 2 T. Faestermann, et al., Prog. in Part. and Nucl. Phys. **69** (2013): 85-130.
- 3 T.D. Morris et al., Phys. Rev. Lett. **120**, 152503 (2018).
- [4] T. Togashi et al., Phys. Rev. Lett. **121**, 062501 (2018).

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## Studies of lanthanide desorption for laser spectroscopic investigations of the heaviest actinides

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Laser spectroscopic investigations on the heaviest elements allow for an understanding of fundamental atomic and nuclear properties. Relativistic and QED effects as well as electron correlation strongly influence the atomic shell. Due to these effects the configuration of the atomic ground state in lawrencium (Lr,  $Z=103$ ) is expected to differ from the iso-electronic homologue lutetium (Lu,  $Z=71$ )<sup>1</sup>. A precise determination of the first ionization potential or a hyperfine structure measurement will help to unambiguously characterize the atomic ground state.

To probe the atomic shell structure of the heaviest actinides with  $Z > 100$ , the sensitive RADIATION DETECTED RESONANCE IONIZATION SPECTROSCOPY (RADRIS) technique is applied at the SHIP velocity filter at GSI. After production in fusion-evaporation reactions the recoil ions are separated from the primary beam, stopped in a buffer-gas cell and collected onto a filament. A subsequent thermal evaporation as neutral atoms allows probing the atomic structure using resonance ionization laser spectroscopy. The photo-ions, which are created in case of resonantly tuned laser radiation, are transported to a silicon detector and identified by their characteristic alpha-decay energy. Only recently and for the first time, an optical ground-state transition in the element nobelium (No,  $Z = 102$ ) was identified<sup>2</sup>.

To extend the technique to the next heavier element Lr, the release of the captured recoils from the filament has to be studied in detail. The nobelium experiment used a tantalum filament for neutralization and evaporation, but first tests indicated that an elevated release temperature is needed for Lr. In combination with the reduced first ionization potential, this results in a surface ionized

background, which hampers the total sensitivity. For evaporation, the desorption enthalpy and the filament work function crucially determine the efficiency and the background created by surface ions, respectively.

In this contribution, a setup for mass spectrometry of surface ionized and laser ionized lanthanides evaporated from different filaments is presented. The desorption of ytterbium and lutetium from different surfaces are discussed with regard to the prospects of laser-spectroscopic investigations of the heaviest actinides.

1 Sato et al., Nature, 520 (2015) 209.

2 Laatiaoui et al., Nature, 538 (2016) 495.

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## Non-destructive isotope analysis of micrometer sized hot particles from the Chernobyl environment by rL-SNMS

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### Introduction

During the accident in the Chernobyl nuclear power plant, high amounts of radionuclides have been released into the environment. Besides volatile elements like iodine and cesium, actinides mostly contained in highly radioactive fragments of nuclear fuel, so-called hot particles, have been distributed in the environment. Depending on composition (highly fired oxides, zirconium containing or rather pure uranium phases) weathering effects and degradation of these particles can be very different and so is the release of radionuclides from these particles. Furthermore, the actinide isotopic distribution is of interest, since it gives insight into the history of the underlying nuclear fuel. To investigate these particles, suitable methods for trace analysis on the microscale are needed.

### Methods

An electron microscope equipped with an EDX detector is used for localization of the hot particle and a micro-manipulator with an attached tungsten needle is used for isolation. The particle is glued to the tip of the tungsten needle and removed from the sample.

Classical isotopic analysis techniques mostly involve the destruction of the hot particle or only focus on one element. Non-destructive analysis of isotopic compositions for trace concentrations of radionuclides in the presence of excessive amounts of uranium dioxide however, is a challenging task. Commercially available time of flight secondary ion mass spectrometers (TOF-SIMS) are suited for analysis of the main element of the particle, however environmental samples typically show a high background of organics and, furthermore, isobaric interferences of U-238/Pu-238 and Pu-241/Am-241, respectively, which prevents the analysis of minor actinides.

These challenges lead to a new approach, which surpasses the commercially available TOF-SIMS. It involves resonant post ionization of secondary neutrals generated in the sputtering process. A tunable Ti:sapphire laser system has been coupled to a TOF-SIMS, to achieve just that.

The secondary neutral cloud is illuminated by laser light tuned to the transition energies of a specific element. This way, atoms of the selected element are resonantly ionized in at least two steps, which results in a very high element selectivity and ionization efficiency. The ions generated already in the sputtering process are suppressed by a pulsed electric field. An isobaric suppression of more than four orders of magnitude regarding U-238 to Pu-238 is achieved.

### Results

A number of particles have been extracted and isolated out of soil samples from the Chernobyl exclusion zone. Analysis of uranium isotopic ratios is available via standard SIMS. By applying the resonant laser ionization to the sputtered atoms, a non-destructive analysis of the isotopic ratios of trace elements becomes possible.

Here, we will present the coupling of the laser system to the TOF-SIMS, as well as results from measurements on hot particles from the Chernobyl exclusion zone for several important radionuclides.

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## Development of a New Laser Ablation Ion Source

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A new laser ablation ion source is under development at Institut für Kernphysik, TU Darmstadt for high-precision collinear laser spectroscopy. It is based on the original idea of RF-only ion funnel 1 for extraction of ablated ions, which are produced in presence of high purity buffer gas, into vacuum. The final cooling and bunching of the extracted ion beams is performed in an additional (RF+DC)-funnel placed downstream 2. Detailed computer simulations have shown that this ion source 3 will allow us to produce various high-quality continuous and pulsed ion beams, with low transverse and longitudinal emittance. The ion-beam properties will be investigated using a compact collinear apparatus. We will present the current status and first results of this project development.

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2 Victor Varentsov, Proposal for a new Laser ablation ion source for LaSpec and MATS testing, NUSTAR Collaboration Meeting, 1 March, 2016, DOI: <https://doi.org/10.13140/RG.2.2.10904.39686>

3 T. Ratajczyk, V. Varentsov and W. Nörtershäuser, Status of a new laser ablation ion beam source for LASPEC, GSI-FAIR SCIENTIFIC REPORT 2017, DOI: <https://doi.org/10.15120/GR-2018-1>

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## Developments of a widely tunable titanium-sapphire laser system for the ARIEL laser ion source

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A new concept for widely tunable Ti:Sa lasers is under investigation for the ARIEL (Advanced Rare IsotopE Laboratory) laser ion source at TRIUMF (Canada's particle accelerator center). Wavelength

selection for pulsed Ti:Sa lasers are usually done with birefringent filters (BRF), etalons or diffraction gratings. For resonance ionisation spectroscopy a laser system allowing a continuous wavelength scan is necessary. Tunable lasers based on BRFs and etalons have high output powers however require synchronised optimisation and are therefore laborious for these operations. Diffraction grating based laser systems overcome these shortcomings yet are limited in input power due to local heating leading to deformation of the grating reducing the overall output power.

Taking all of that into account a laser system is developed which is composed of several prisms using their dispersive quality for splitting the laser beam into its spectrum and selecting the wavelength through a motorised mirror. Simulations on the beam path and reflection losses are done. The results show that for a rigid prism system an alignment can be found in which the reflection losses do not exceed 0.14 % in a wavelength range of 420 nm for p-polarised light. A tuning range of 220 nm was reached with a gain of 18 % and a linewidth of 12 GHz. The beam path deviation depending on the wavelength differs by around 5° leading to an easy and accurate wavelength selection. Further testings of various configurations are still ongoing. Investigations include different prism materials and pumping sources as well as changes in quantity of prisms and a computer operated aperture for linewidth reduction.

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## Resonance laser ionization of neutron-deficient silver isotopes

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The radioactive neutron-deficient silver isotopes around the  $N=Z$  region have been of considerable interest for several years. A multitude of phenomena may be expected to be exhibited by these isotopes due to their proximity to the  $N=Z$  line; enhanced proton-neutron correlations may play an important role; the astrophysical rapid-proton (rp) process passes through this region; strong shell-correction effects may be expected due to the doubly-magic  $N=Z=50$  shell closure. In particular, the isotope  $N=Z$   $^{94}\text{Ag}$  may exhibit the most unique isomer in existence. In addition to a low-spin (7+) beta-delayed proton-decaying isomer,  $^{94}\text{Ag}$  has been identified as having a spin trap isomer with the highest spin, (21+), ever observed for  $\beta$ -decaying nuclei. The isomer's long half-life of 0.39(4) s, high excitation energy and high spin are matched by an unparalleled selection of decay modes including, among others,  $\beta$  decay and one-proton [4] decay. However, the most exotic form of decay that has been claimed to exist in  $^{94m}\text{Ag}$  (21+) is two-proton emission.

The existence of the two-proton decay mode in  $^{94}\text{Ag}$  was questioned [5] due to the non-observation of states in  $^{92}\text{Rh}$  that were supposedly populated and thus used as evidence for the decay. Furthermore, mass measurements of  $^{92}\text{Rh}$  and  $^{94}\text{Pd}$ , the respective two-proton and  $\beta$ -decay daughters of  $^{94}\text{Ag}$ , have been performed at JYFLTRAP which, when combined with the original spectroscopic decay data, lead to a contradiction [6] in the isomer energy. To solve the conundrum, direct mass measurements of  $^{93}\text{Pd}$  (the 1-proton decay channel),  $^{94}\text{Ag}$  and  $^{94m}\text{Ag}$  (21+) are needed which will allow unambiguous determination of the energy of isomer.

Here we present the recent results and outlook for a dedicated project aiming to selectively produce low-energy radioactive beams of  $^{94}\text{Ag}$  for mass measurements at IGSOL using an inductively-heated hot cavity catcher ion source. The latest design of the device was commissioned in an experiment in May 2018 whereby the total efficiency of the hot cavity laser ion source was determined to be of the order of ~1%. Furthermore, resonant laser ionization spectroscopy was demonstrated for  $^{97-104}\text{Ag}$ , including isomer-selective ionization made possible due to the large hyperfine splitting in the high-spin states.

- 1 I. Mukha et al., Physical Review C 70, 044311 (2004).
- 2 I. Mukha et al., Nature 439, 298 (2006).
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- [4] I. Mukha et al., Physical Review Letters 95, 022501 (2005).
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- [6] A. Kankainen et al., Physical Review Letters 101, 142503 (2008).

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## Towards the Ion Mobility Measurement of Actinides

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Ion mobility studies are a powerful tool to investigate ion-atom interaction potentials. Their sensitivity to the electronic configuration has been proven for various elements across the periodic table. Especially for heavy elements, the impact of relativistic effects on the electronic configuration of singly ionized atoms may lead to deviations in the periodicity, hence to distinct ion mobilities. This opens up a new niche for isobaric purification and element identification in the research of actinides and transactinides. Systematic ion mobility spectrometry measurements performed in the lanthanides 1 are being extended to the actinides. An ion mobility spectrometer (IMS), consisting of a gas-filled drift section and an extraction section containing an RFQ-ion-guide and a quadrupole mass filter, enables the user to provide an element-selective ion production from a sample filament by resonant two-step laser ionization and thus ensure an element-selective detection. Especially the region from Pu (Z=94) to Cf (Z=98) will be covered by future experiments due to a predicted distinction in the electronic configurations 2. In the poster, the experimental approach, the first results and the future plans are presented.

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2: Indelicato, P. et al., EPJD(2007) 45:155

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## High-resolution laser spectroscopy of neutron-deficient indium isotopes

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Recent developments at the Collinear Resonance Ionisation Spectroscopy (CRIS) experiment at ISOLDE, CERN 1 have allowed for high-precision determination of electric-quadrupole moments, magnetic-dipole moments and changes in mean-square charge radii of ground and long-lived isomeric states in the neutron-deficient indium ( $Z = 49$ ) isotopes,  $^{101-115}\text{In}$ . Experimental linewidths of <50 MHz were achieved at production yields of  $10^3$  particles/s.

Prior to the radioactive beam experiment, the sensitivity to nuclear observables of atomic states in indium was investigated using the CRIS ablation ion source. The  $5p^2P_{3/2}$  to  $9s^2S_{1/2}$  transition (246.8 nm) was shown to provide sufficient sensitivity within the available experimental time frame 2. This transition was used online in combination with the  $5p^2P_{1/2}$  to  $8s^2S_{1/2}$  transition (246.0 nm) to unambiguously separate ground and isomeric hyperfine-structure peaks, and to further constrain nuclear spin assignments.

These measurements provide an important benchmark in the development of many-body methods, which are now able to predict properties around the  $Z = N = 50$  shell-closures [3,4]. States in previously measured odd-even indium isotopes have shown a remarkably constant single-particle behaviour; whether this trend in the electromagnetic moments continues will give insight into the strength of the shell closures. Isomeric spin assignments in the odd-odd isotopes also help pin down the ordering of the neutron  $d_{5/2}$  and  $g_{7/2}$  orbits [5,6].

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## Highly Efficient and Sensitive Resonance Laser Ionization of Pu

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Plutonium is the most important transuranium element because of its use as fuel in nuclear reactors and its use in nuclear weapons. Detection of  $^{244}\text{Pu}$  in deep-sea sediments on Earth also could provide important insight to understand the nucleosynthesis of heavy elements 1. Ultra-trace analytical techniques such as Accelerator Mass Spectrometry (AMS) have been used to measure the abundance of  $^{244}\text{Pu}$  in deep-sea reservoirs on Earth 2. However this technique using Cs-sputtering sources has relatively low efficiency for actinides 3. We have explored Resonance Ionization Mass Spectroscopy (RIMS) for plutonium detection. We conducted spectroscopy studies to search for new efficient ionization schemes. New three-step ionization schemes for Pu have been developed. Using calibrated Pu samples and the Injector for Radioactive Ion Species 2 setup at ORNL, an overall ionization efficiency of 51% for Pu has been measured. Using a mixed isotopic Pu sample that contained

only  $5 \times 10^3$  atoms of  $^{240}\text{Pu}$ , which corresponds to about 0.002 fg,  $^{240}\text{Pu}$  ions were cleanly separated from ions of other Pu isotopes and counted.

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## Tests of Bound-State QED using Ramsey-Comb Spectroscopy on $\text{H}_2$ and $\text{He}^+$

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In 2010, the spectroscopic measurement of the Lamb shift in muonic hydrogen initiated the so-called proton radius puzzle. The extracted proton charge radius showed a  $5\sigma$  discrepancy with the CODATA-2010 value, which is mainly based on spectroscopy in electronic hydrogen and electron scattering of protons [1]. In recent years, more measurements have been performed, which do not agree on the value of the proton charge radius [2,3]. In order to contribute to solving this puzzle, we investigate two different systems, molecular hydrogen and singly ionized helium. Alternatively, they provide a great testing ground for bound-state quantum electrodynamics (QED).

In  $\text{H}_2$ , we measured the  $\text{EF} \leftarrow \text{X}(0,0) \text{Q}_1$  transition with an accuracy of 73 kHz using Ramsey-comb spectroscopy [4]. We are now preparing a measurement of the  $\text{EF} \leftarrow \text{X}(0,0) \text{Q}_0$  transition (para- $\text{H}_2$ ) and improved the laser system and the molecular beam to reach a targeted accuracy of 10 kHz. Combined with additional transitions measured in the group of Prof. Merkt, the dissociation energy ( $D_0$ ) of para- $\text{H}_2$  can be determined, from which the proton radius can be extracted. Furthermore, we will combine measurements of two transitions from different initial vibrational states to determine the fundamental ground tone, which can be calculated with high accuracy from first principles.

In  $\text{He}^+$ , we aim to measure the two-photon  $1\text{S}-2\text{S}$  transition with an accuracy of 1 kHz using unequal photons (32 + 790 nm). When combined with other measurements, we can either improve current QED tests, determine a new value for the Rydberg constant or determine the charge radius of the alpha particle. A single helium ion is trapped in a linear Paul trap and is sympathetically cooled with a beryllium ion. After excitation of the transition with the Ramsey-comb method (based on two amplified and upconverted frequency-comb pulses), the state is read out via  $\text{Be}^+$  using a quantum logic-type scheme. We are currently testing Ramsey-comb spectroscopy in combination with high-harmonic generation on the  $5\text{p} \rightarrow 8\text{s}$  transition in xenon at 110 nm (the 7<sup>th</sup> harmonic of the fundamental). Preliminary results show that we can determine the transition frequency with an accuracy of 1 MHz ( $d\nu/\nu < 5 \cdot 10^{-10}$ ), which is mainly limited by the transit time of xenon atoms through the refocused VUV beam. This shows great promise for the measurement in  $\text{He}^+$ , because motional effects can be strongly reduced for a trapped ion.

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## Astatine - The rarest element on Earth: From laser spectroscopy to fundamental atomic properties

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The radioactive element astatine (At) is the rarest naturally occurring element on Earth. Certain isotopes of this enigmatic element possess decay characteristics which render them particularly suitable for cancer treatment through targeted alpha therapy. Natural astatine exists predominantly in the form of <sup>218</sup>At, with a half-life of only two seconds. Its abundance is maintained by the radioactive decay of natural <sup>238</sup>U, but its scarcity prohibits the use of these atoms for the study of even basic properties of the element. Instead, artificial production of astatine isotopes through nuclear reactions is required to obtain samples large enough for study of its atomic properties in the laboratory. Of primary interest for our study are the ionization energy and electron affinity. These two fundamental characteristics determine the bond strengths and therefore the chemical behaviour of astatine and its use in radiopharmaceuticals. The experimental programme to measure these two properties of astatine at the ISOLDE radioactive isotope facility at CERN will be presented.

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## Predicting Atomic Properties of Superheavy Elements

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Advances in laser spectroscopy of superheavy ( $Z > 100$ ) elements enabled determination of the nuclear moments and differential mean-square charge radii of the heaviest nuclei, which required high-precision atomic calculations of the relevant hyperfine structure constants and isotope shifts [1,2]. The calculations of atomic properties of No, Lr, and Rf and their ions using high-precision hybrid approach combining linearized coupled-cluster and configuration interaction methods are reported [2,3]. I will focus on the recent and future methodology developments and capability of the state-of-the-art atomic methods to treat heaviest elements. The methods to evaluate the accuracy of theoretical predictions are discussed.

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## Analysis of actinides and fission products in spent nuclear fuel by resonance ionization mass spectrometry

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Modern nuclear forensic and nonproliferation research requires ever more sensitive and versatile analytical methods. For many years mass spectrometry, in tandem with radioanalytical methods, has played a key role in nuclear forensics, i.e., the determination of the provenance and intended use of nuclear material found outside regulatory control. More recently, we have developed advanced Resonance Ionization Mass Spectrometry (RIMS) techniques to characterize spent nuclear fuel for nonproliferation purposes, e.g., to determine the amount and grade of plutonium produced in a nuclear reactor. In addition, the isotopic compositions of a suite of actinides and fission products in irradiated fuel can potentially provide valuable information on reactor operation history for comparison with declared activity. Because spent fuel is extremely radioactive, analytical methods that can extract the maximum amount of information from the smallest quantities of material with as little sample handling as possible are particularly valuable.

RIMS is an efficient and powerful method of isotopic analysis for a variety of materials. In this talk we discuss recent developments in the application of RIMS to spent nuclear fuel from a holistic point of view, with an eye to maximum information return from minimum sample volumes of solid fuel particles. We discuss the particular challenges of vaporizing solid spent fuel inside the mass spectrometer in a way that maximizes the efficiency of the subsequent laser ionization step in order to reduce sample consumption. We compare ion sputtering techniques with nanosecond and femtosecond laser ablation and discuss the advantages and utility of each. We present several new laser spectroscopic schemes for actinide and fission product analyses. Several different U, Pu and Am resonance ionization and laser pulse timing schemes were developed to solve various problems in spent fuel actinide analysis, such as the resolution of  $^{238}\text{U}$  /  $^{238}\text{Pu}$  and  $^{241}\text{Pu}$  /  $^{241}\text{Am}$ . New methods were also developed for the analysis of fission products such as  $^{88,90}\text{Sr}$ ,  $^{85,87}\text{Rb}$ ,  $^{96,97,98,100}\text{Mo}$  and  $^{137,138}\text{Ba}$ . Some of these can be analyzed simultaneously using the new methods, thereby reducing the amount of material required to characterize a sample. Finally, we combine actinide RIMS with Secondary Ion Mass Spectrometry (SIMS) of fission product Cs ( $^{133,135,137}\text{Cs}$ ) to extract further information without extra sample consumption.

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## **Spectroscopy of the molecular ion HD<sup>+</sup> in the Lamb-Dicke regime: towards determination of fundamental constants at the $10^{-10}$ level**

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(First and last paragraph of the summary)

Precision measurements with cold atoms and molecules allow testing the predictions of quantum

electrodynamics, determining fundamental constants, probing their possible time variation, and searching for

new fundamental interactions. The effective control of atoms' and molecules' external and internal degrees of

freedom paves the way to increased accuracy. Molecular hydrogen ions (MHIs) are three-body quantum systems

for which comparison of ab initio theory and experiment can provide an independent determination of the

Rydberg constant, of the mass ratios of electron to proton and electron to deuteron, and ultimately also of the

proton's and deuteron's charge radius. This program is enabled by recent strong advance in ab initio theory,

which has reached  $\approx 1 \times 10^{-11}$  inaccuracy.

...

With a novel spectroscopic approach we are able to test the recently improved theory of the spin structure of the molecular

ion at the 0.1 kHz uncertainty level. We are also currently analysing the data towards determining the

fundamental constant  $R_\infty m_e (m_p^{-1} + m_d^{-1})$  with a goal uncertainty in the low- $10^{-10}$  range. Our value can then be

compared with the combined results from atomic hydrogen spectroscopy and mass spectrometry in Penning traps

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## Quantum Logic Spectroscopy of Highly-Charged Ions

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Outer electrons in highly charged ions (HCI) show extreme properties in comparison to those of atoms. Their narrow optical fine-structure transitions have smaller polarizabilities and electric quadrupole moments, but much stronger relativistic, QED and nuclear size contributions to their binding energy. Consequently, they have been proposed as future clock candidates and to probe for physics beyond the Standard Model. Specifically, HCI offer the most sensitive transitions of any known atomic system to a change in the fine-structure constant 1. HCI can readily be produced and stored in an electron beam ion trap (EBIT). There, the most accurate laser spectroscopy on any HCI was performed on the 17-Hz wide fine-structure transition in  $\text{Ar}^{13+}$  with 400-MHz resolution, limited by Doppler broadening in the EBIT. The lack of a suitable optical transition for laser cooling and detection can be overcome through sympathetic cooling with a co-trapped  $\text{Be}^+$  ion 2. Techniques developed for quantum information processing with trapped ions can be used to perform quantum logic spectroscopy 3: A series of laser pulses transfers the internal state information after spectroscopy onto the  $\text{Be}^+$  ion for efficient readout.

I will present how HCI can be extracted from a compact EBIT [4], charge-to-mass selected and injected into a cryogenic Paul trap containing a crystal of laser-cooled  $\text{Be}^+$  ions. By removing excess  $\text{Be}^+$  ions, a crystal composed of a  $\text{Be}^+/\text{Ar}^{13+}$  ion pair can be obtained. First results on sympathetic ground state cooling and quantum logic spectroscopy of the  $\text{Ar}^{13+} P_{1/2}-P_{3/2}$  fine-structure transition at 441 nm will be presented, improving the resolution by more than six orders of magnitude.

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## Quantum computing with trapped ions as a technology backbone for precision measurement in fundamental science

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Quantum technologies allow for fully novel schemes of computing, simulation and sensing. For quantum computing, we employ trapped ions in modern segmented ion traps as scalable and freely reconfigurable qubit register 1. I will give an overview of the recent progress, where gate fidelities of 99.995% (single bit) and 99.6% (two bit) are reached and complex gate sequences are currently implemented for topological quantum error correction 2. The relevant techniques, such as building and operating multi-segmented micro ion traps, shuttle operations 3, ground state and sympathetic cooling, precision compensation of magnetic fields and magnetic field gradients [4,5] add to a toolbox which is readily available for future studies on single exotic atoms such as rare isotopes of Thorium ions [6] or anti-Hydrogen ions [7].

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## High-Precision Mass Measurements with PENTATRAP

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High-precision mass-ratio measurements with relative uncertainties below  $10^{-11}$  have applications, among others, in tests of the theory of special relativity (SRT) 1, bound-state quantum electrodynamics (QED) 2 and neutrino physics research [3, 4]. This precision is achievable in Penning-trap mass spectrometry, where the mass of a charged particle is determined by measuring its free cyclotron frequency in a strong magnetic field.

With the first proof-of-principle mass-ratio measurements of xenon isotopes the novel high-precision Penning-trap mass spectrometer PENTATRAP [5], located at the Max-Planck-Institut für Kernphysik in Heidelberg, has recently demonstrated a relative mass-ratio precision of  $10^{-11}$  using highly charged xenon ions. Unique features of the setup are the use of electron beam ion traps [6, 7] as external ion sources and a stack of five cylindrical Penning traps [8]. This allows for simultaneous storage and measurement of several ion species, reducing systematic errors. Long storage times due to a cryogenic environment and dedicated image current detection systems [9] with single ion sensitivity allow for high-precision determination of the cyclotron frequencies in all traps.

Our next measurements will concentrate on nuclides relevant for neutrino physics research, such as  $^{187}\text{Re}$  and  $^{163}\text{Ho}$  [3, 4]. Preliminary results of the current measurements of xenon isotopes, the present status of the experimental setup of PENTATRAP and future projects will be presented.

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## In-source laser photoionization spectroscopy of very neutron-deficient Bi isotopes: new example of nuclear shape staggering

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Understanding shape evolution and shape coexistence in atomic nuclei is one of the greatest challenges faced by theories of nuclear structure. The neutron-deficient isotopes near  $Z = 82$  exhibit the richest manifestation of shape evolution and shape coexistence phenomena. The behavior of the ground and isomeric states shape differs markedly for different  $Z$  in this region. While in the Hg isotopic chain ( $Z = 80$ ) jump-like odd-even shape staggering was observed at  $N = 101-105$  (see Ref.1 and references therein), for Po nuclei ( $Z = 84$ ) an early onset and gradual increase of deformation

were found at  $N < 113$ . At the same time the neutron-deficient Pb ( $Z = 82$ ) nuclei remain essentially spherical in their ground states, up to and beyond the neutron mid-shell at  $N = 104$ .

This contribution will discuss the charge radii and electromagnetic moments of neutron deficient Bi isotopes ( $N = 104 - 108$ ) measured at ISOLDE (CERN) facility using the in-source laser photoionization spectroscopy in the framework of IS608 collaboration. A large odd-even staggering in charge radii was observed at  $N = 105$ . The similar effect was previously observed only in the Hg isotope chain. In contrast to laser spectroscopy of strongly deformed Hg isotopes with nuclear spin  $I = 1/2$ , the deformation parameter for Bi isotopes can be extracted from the measured electric quadrupole moment  $Q_s$ . Moreover, our data enable us to revise the spin assignment for deformed ground state of Bi-188.

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## MIRACLS: A Multi Ion Reflection Apparatus for Collinear Laser Spectroscopy

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Laser spectroscopy is a well-established technique for studying nuclear ground-state properties in a model-independent way. It provides access to the charge radii and electromagnetic moments of the nuclear ground state as well as of isomers by observing the isotope shifts and hyperfine structures of the atoms' spectral lines [1, 2]. While in-source laser spectroscopy in a hot cavity is a very sensitive method that is able to measure rare isotopes with production rates below one particle per second [3], the spectral resolution of this method is limited by Doppler broadening to ~5 GHz. Collinear laser spectroscopy (CLS) on the other hand, provides an excellent spectral resolution of ~10 MHz [1] which is of the order of the natural line widths of allowed optical dipole transitions. However, CLS requires yields of more than 100 or even 10,000 ions/s depending on the specific case and spectroscopic transition [4].

The MIRACLS project at CERN aims to develop a laser spectroscopy technique that combines both the high spectral resolution of conventional fluorescence CLS with an enhanced sensitivity factor of 20-600 depending on the mass and lifetime of the studied nuclide. The sensitivity increase is derived from an extended observation time provided by trapping ion bunches in a Multi-Reflection Time-of-Flight device where they can be probed several thousand times [5]. A proof-of-principle

apparatus, operating at 2 keV beam energy, has been assembled at CERN ISOLDE with the goal of demonstrating the MIRACLS concept, benchmark simulations [6] that will be employed to design a future device operating at 30 keV and further technological developments.

Recently, first measurements have been performed with the proof-of-principle apparatus using stable magnesium isotopes as a first test case. Laser spectroscopy has been performed on  $^{24,26}\text{Mg}$  isotopes trapped for more than 1000 revolutions in the MR-ToF and isotope shifts have been determined. Line widths close to the Doppler limit in this 2-keV machine have been achieved. An extensive characterizing study of the device is ongoing.

This talk will introduce the MIRACLS concept, present the first results and current status of the project as well as an outlook towards further developments.

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## A Collinear Laser Spectroscopy Beamline at Argonne National Laboratory

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Collinear Laser Spectroscopy (CLS) is a well-established technique at modern research facilities. In combination with different isotope production and separation methods, nuclear properties for a remarkable fraction of the nuclear chart have been studied. To further extend the capabilities of this technique, we are commissioning a CLS beamline at Argonne National Laboratory. Here, the new CARIBU Californium fission source opens up a vast area of interesting isotopes for collinear laser spectroscopy. This includes in particular neutron rich refractory metals that have not been studied so far. Also, a target section installed at the ATLAS accelerator provides a low-energy Boron-8 beam. With the new CLS beamline, the charge radius of Boron-8 can be investigated to confirm its proton halo character.

We present the status of this project as well as technical advances to optimize the capabilities of this collinear spectroscopy experiment: A newly designed optical detection system provides improved sensitivity, especially for low-yield experiments. First results have shown the effectiveness of this new detection system during recent experiments at the KOALA beamline in Darmstadt and the BECOLA setup at NSCL. The beamline also features a new charge exchange cell, which is designed for the use of alkali and alkali-earth vapors at high temperatures and the operation at high voltages. Furthermore, in preparation of the boron-8 experiment, a molecule breakup station, utilizing few-nanometer carbon foils, has been installed. Boron-8 is produced with high rates in the  $^7\text{Li}(^3\text{He},n)^8\text{B}$

reaction and successfully stopped in a gas catcher system, but radioactive molecules are formed in the cooldown process. The molecules are broken up while travelling through the carbon foil and the resulting pure  $^8\text{B}$  ions can afterwards be collected and extracted in a RFQ cooler-buncher.

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## A Laser system for fluorescence imaging of $\text{He}_2^*$ excimers generated by the $^3\text{He}$ neutron absorption reaction.

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Metastable  $\text{He}_2^*$  excimers are a promising tracer<sup>1</sup> for the investigation and visualization of the superfluid  $^4\text{He}$  velocity distribution for studies in the encompassing field of Quantum turbulence. For full 3D flow-field mapping a distributed cloud of localized clusters of the excimer would be required, which may be generated via the  $^3\text{He}(\text{n},\text{p})^3\text{T}$  neutron absorption reaction. The energetic recoils of the reaction create a short track of ionized and excited Helium atoms, which finally result in a cluster of approximately 10000 excimer molecules. Due to their relatively long lifetime of 13 s they can be used for fluorescence applications.

One particular excitation scheme uses a near-resonant two-photon process from the excimer ground state at  $\lambda = 905$  nm to the excited state  $d^3\Sigma_u^+$ , after which fluorescence at 640 nm is emitted, giving a near background-free signal if using spectral bandpass-filtering.

Two-photon transitions require high pulse energy and short pulse duration for efficient excitation. A simple approach for generation of such pulses is the use of a reduced laser cavity length. A Ti:sapphire laser cavity with an optical path-length of 4 cm is demonstrated, using a two-prism tuner for wavelength selection. Pulses of > 1mJ energy with pulse duration below 3 ns at 905 nm were produced using a low repetition rate flashlamp-pumped YAG laser as pump source. In addition to the Ti:sapphire, two continuous wave diode lasers at 1064 nm and 1085 nm are employed for repumping from trap states. The whole system was mounted on a  $60 \times 70$  cm<sup>2</sup> optical breadboard for ease of transportation.

In a recent experiment (2018) at the J-PARC facility the system was used in combination with photomultiplier tubes for detection of the fluorescence signal, with which the neutron generation mechanism could be verified for the first time<sup>2</sup>. In an upcoming second experiment at J-PARC in March 2019, imaging of the excimer clusters will be attempted using an improved laser setup and a high sensitivity camera.



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## A direct diode pumped continuous wave Ti:sapphire laser seeding a pulsed amplifier for high resolution Resonance Ionization Spectroscopy

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Laser spectroscopy and ionization are well established tools for the analysis or production of radioactive ion beams. New developments such as ionization in a supersonic gas jet<sup>1</sup>, perpendicular ionization geometries (PI-LIST)<sup>2</sup> or Collinear Resonance Ionization (CRIS)<sup>3</sup> have been demonstrated with impressive results. In these techniques the minimization of transition line broadening effects from pressure or temperature yields enhanced resolution for hyperfine spectroscopy or isotope shift measurements of various elements. This in turn allows the determination of important nuclear parameters such as magnetic/electric nuclear moments or changes in mean-square charge radii. Furthermore, high resolution spectroscopy results in improved ionization selectivity and thus the possibility of trace analysis and nuclear beam purification for experimental stations further down the beam-line.

For ideal performance these techniques require pulsed, spectrally narrow laser sources. Amplification of a narrow-band seed source in an injection-locked Ti:sapphire(Ti:sa) amplifier results in high intensity pulses, combined with a spectral linewidth below 20 MHz[4].

Seed lasers such as external cavity diode lasers (ECDL) are limited by tuning range and output power, while commercial cw-Ti:sa systems are prohibitively expensive for many smaller laboratories. The recent availability of high-performance green-blue diode lasers promises to replace the traditional expensive cw-Nd:YAG pump laser technology for Ti:sa[5]. This opens the opportunity to develop a cw-Ti:sa at a significantly lower price point. A prototype system has been set up, using two diodes at 465 nm and 520 nm. The diode output power and beam profile was investigated. A maximum Ti:sa output power of 1 W was realized and a tuning range of 725-880 nm of the Ti:sapphire bow-tie ring resonator was achieved using a birefringent filter and etalon combination, limited by the used mirror-coatings. Single-mode emission was confirmed using a Fabry-Perot Interferometer. Unidirectional emission was forced using a home-built optical diode based on a Brewster-cut TGG crystal and  $\lambda/2$  waveplate. Frequency stabilization and mode-hop free scanning capability are currently still in development.

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## When conventional NMR is not enough: Applications of $\beta$ -NMR in chemistry, biology and medicine

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on behalf of the bio- $\beta$ -NMR collaboration at TRIUMF

Many processes in nature are governed by the interaction of biomolecules with metal ions. Some biologically highly relevant metal ions, such as  $Mg^{2+}$ ,  $Cu^{+}$  and  $Zn^{2+}$ , are silent in most spectroscopic techniques, rendering characterization of their biological function difficult. Therefore, there is a demand for new experimental approaches to directly study these metal ions.

$\beta$ -radiation detected nuclear magnetic resonance ( $\beta$ -NMR) spectroscopy has already been applied multiple times to liquid samples at the ISAC facility at TRIUMF, Canada's particle accelerator center. In contrast to any previously reported measurements, the resonance spectra recorded for  $^{31}Mg^{+}$  implanted into solutions of different ionic liquids displayed well-resolved resonances originating from oxygen and nitrogen coordinating  $Mg^{2+}$  ions in different complexes, as well as biologically relevant molecules 1. The recorded resonance line widths are very narrow, and in most cases exceed the ones reported for conventional NMR spectroscopy on similar systems, underlining the complementary advantages of  $\beta$ -NMR. Furthermore, just recently  $\beta$ -NMR has also been applied to study  $Mg^{2+}$  binding to ATP –the energy currency of life - in solution. This achievement not only marks a milestone in applications of  $\beta$ -NMR in liquid samples, but also allows to answer the long-standing question of  $Mg^{2+}$  coordination to ATP 2.

Results from the recent  $\beta$ -NMR experiments with  $^{31}Mg^{+}$  ions in solution performed at TRIUMF [1,3] and the future plans will be presented and discussed

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## Towards online isotope separation at iThemba LABS, South Africa

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The development of the South African Isotope Facility at iThemba Laboratory for Accelerator Based Science (LABS) has the goal of producing isotopically pure radioactive-ion beams for basic research and applications. Delivery of 60 keV radioactive ion beams from reactions produced by 66 MeV protons on various targets, including uranium carbide is planned. Its development complements the South African involvement at international facilities to advance the interdisciplinary field on the interface between laser spectroscopy and nuclear research in Southern Africa. Realisation of the first phase, a Low-Energy Radioactive-Ion Beam facility, is planned over a four year time scale.

We report on progress achieved in offline experimental test setups as well as numerical simulations

in preparation for the future online facility. A setup for atomic beam resonance ionisation spectroscopy is combined with reflectron-time-of-flight mass spectrometry at the Laser Research Institute. Whereas spatial mass separation will be the choice for applications, the reflectron-time-of-flight mass spectrometer yields a full mass spectrum per laser pulse that makes it possible to investigate the effect of changes on all isotopes and contaminants simultaneously. Numerical simulations and experimental results on the stable isotopes of Sn, as test element, are combined to investigate and optimise experimental conditions. Investigation of nonlinear and potential Doppler-free techniques are planned.

At iThemba LABS the combination of a tunable Ti:Sa laser system and a full scale hot-cavity ion-source front-end are being developed. Design considerations and offline tests will be discussed. Modification of the future online front-end for carbonyl extraction of refractory elements.

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## Hyperfine puzzle of strong-field bound-state QED

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The specific difference between the ground-state hyperfine splittings in hydrogen-like and lithium-like ions of the same isotope,

$$\Delta' E = \Delta E^{(2s)} - \xi \Delta E^{(1s)},$$

was suggested about fifteen years ago as an alternative tool to prove bound-state QED in the strong magnetic field generated by a heavy nucleus <sup>1</sup>.

The isotope in these charge states has hyperfine splittings with transition wavelengths very close to the visible spectrum and therefore they can be probed by laser spectroscopy. The  $1s$  hyperfine splitting in hydrogen-like  $^{209}\text{Bi}^{82+}$  was measured by direct laser spectroscopy at the experimental storage ring (ESR) at the GSI Helmholtz-Center for heavy ion research in Darmstadt in 1994 <sup>2</sup>. Seventeen years later by using an improved laser spectroscopy technique at the same storage ring we found the  $2s$  hyperfine splitting in lithium-like  $^{209}\text{Bi}^{80+}$  <sup>3</sup>. Combined with a new measurement of the  $1s$  hyperfine splitting in the hydrogen-like we found a good agreement with the corresponding theoretical prediction. Yet the accuracy of our result at that time was limited by the calibration of the electron cooler voltage, use to determine the velocity of the ions revolving in the storage ring.

We have now repeated this experiment with an in-situ voltage measurement and achieved accuracies at the  $10^{-5}$  level for both transitions, the most accurate transition wavelengths measured so far in a

heavy highly charged ion. From these measurements we have extracted the specific difference and found a more than  $7\sigma$  deviation from the strong-field bound-state QED prediction [4].

Recent NMR measurements on bismuth have provided an evidence that this issue is caused by a wrong magnetic moment of this nucleus in literature [5,6].

To finally solve the hyperfine puzzle we are considering now to extend these measurements to the neighboring isotopes of bismuth and to measure the respective transitions additionally with a considerably improved accuracy in a Penning trap [7].

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## Development of Radiocarbon Analysis System with Mid-Infrared Cavity Ring-down Spectroscopy for Biological and Environmental Tracer Applications

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Radioactive carbon (C-14) is widely used as a tracer in various research fields due to its ultra-low natural abundance, at about one part per trillion (ppt) and long half-life of 5370 years. In biological and environmental tracer applications using C-14 labeling sensitivity close to natural abundance is required with higher throughput and cost efficiency. Conventional methods such as Accelerator Mass Spectrometry (AMS) and Liquid Scintillation Counter (LSC) are inadequate for this purpose. As alternative, we have developed a radiocarbon analysis system based on Cavity Ring-Down Spectroscopy (CRDS) which is known as one of the most sensitive laser absorption spectroscopic techniques employing a highly reflective resonator.

A prototype system was constructed using a mid-infrared distributed feedback quantum cascade laser with center wavelength at 4.5  $\mu\text{m}$  close to a fundamental absorption line of C-14 carbon dioxide. A good agreement with the concentration of C-14 in the sample was attained and detection limit close to 10 ppt was determined. An animal pharmacokinetics investigation was demonstrated successfully. In addition, we investigated application of our system to C-14 tracer analysis in study of plant carbon dynamics. We designed and constructed a sample pre-treatment unit for efficient injection of plant samples as well as a C-14 labeling unit. C-14 ratio measurements in root and shoot samples were evaluated for carbon dynamics investigation in rice plant.

## Characterization and search for optical excitation of the nuclear clock isomer $^{229m}\text{Th}$

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The  $^{229}\text{Th}$  nucleus possesses a unique first excited state at an energy of only about 7.8 eV, coupled to the ground state by a magnetic dipole transition with a natural linewidth in the mHz range.

An optical clock based on this transition would be highly immune to field-induced frequency shifts and

a sensitive probe of temporal variations of fundamental constants 1.

We recently performed the first measurement of fundamental nuclear properties of this isomeric state,

namely its magnetic dipole and electric quadrupole moments and the mean square charge radius 2. This

was achieved via high-resolution laser spectroscopy of the hyperfine structure of trapped  $^{229}\text{Th}^{2+}$  ions. These ions were loaded from the  $\alpha$  decay of  $^{233}\text{U}$ , which populates the isomeric state via a 2% branching ratio. Hyperfine spectroscopy can therefore now be used as an optical detection method for the isomeric state.

One missing link to study the nuclear transition as a precise clock is the optical excitation of the isomer.

We are now preparing an experiment to investigate the excitation of the nucleus via electronic bridge and

NEET processes [3,4] using two-step laser excitation in  $\text{Th}^{2+}$ .

We are currently investigating the excitation of selected suitable levels in the energy range from 9.3 to

10.3 eV in  $^{232}\text{Th}$ . This isotope is used for initial tests since it is naturally occurring and has no nuclear spin. Populating these electronic states in  $^{229}\text{Th}$  offers coupling possibilities to the isomeric state for nuclear excitation energies from 7.2 to 10.3 eV.

This work is supported by Horizon 2020 grant agreement No. 664732 (nuClock) and by DFG through CRC 1227 (DQ-mat, project B04).

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## Development of frequency comb based laser absorption/ionization spectroscopy of radioactive isotopes

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High-resolution laser absorption and ionization spectroscopy are widely applied to investigate nuclear structure of short-lived radioactive isotopes and trace determination of long-lived radioactive isotopes. Measurement of laser frequency with less than MHz accuracy will be expected to open new possibilities for further understanding of nuclear structure and improvements in trace isotope determination. We have been developed two types of a frequency comb based laser spectroscopic system: mid-IR Cavity Ring-Down Spectroscopy (CRDS) and high-resolution Resonance Ionization Spectroscopy (RIS) of radioactive isotopes. A prototype CRDS system using a mid-infrared distributed feedback quantum cascade laser was developed for radioactive carbon analysis in biomedical samples. To improve abundance sensitivity and precision in isotope ratio, direct calibration and stabilization of frequency of the quantum cascade laser using a fs fiber based mid-IR optical frequency comb was demonstrated. Toward high resolution RIS on PALIS at RIKEN, we investigated high-resolution RIS of stable Zr isotopes using an off-line setup at Nagoya University including an injection locked Ti:Sapphire laser calibrated by a fs fiber based near-IR optical frequency comb. Details in the frequency comb based CRDS and RIS will be discussed in the presentation.

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## Development of Multi-element/isotope Analysis with Resonance Ionization Mass Spectrometry and Resonant Laser Secondary Neutral Mass Spectrometry

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In decommissioning of the Fukushima Daiichi nuclear power station, inventory analysis of samples including radioactive isotopes are demanded to ensure safe and secure control of radioactive waste.

Since origin and history of these samples are unknown in most cases, it is often difficult to make effective pre-treatment before the analysis. To assess the radionuclide inventory of the materials quantitatively, we have developed trace isotope analysis with resonant ionization mass spectrometry (RIMS). Elemental selective ionization via resonance excitation of free atoms by lasers leads to reduced pre-treatment requirements in the analysis with RIMS. To achieve multi element analysis with RIMS, rapidly switching between ionization schemes was demonstrated using two automated grating type Ti:Sapphire laser systems with intracavity SHG in short time frames and within one sample. Although spatial shift of output beam was caused by different walk-off in a SHG crystal during wavelength tuning of the laser, spatial overlapping of both laser pulses was compensated by feedback control of transportation mirrors and a glass plate.

We also successfully demonstrated micro-imaging of radioactive  $^{135}\text{Cs}$  and  $^{137}\text{Cs}$  isotopes on a single environmental particle collected at Fukushima with Secondary neutral mass spectrometry (SNMS) using multicolor post resonance ionization by the automated grating type Ti:Sapphire laser systems, named resonant laser SNMS.

Details of the automated grating type Ti:Sapphire laser system and its applications to RIMS/resonant laser SNMS will be discussed in the presentation.

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## First $g$ -Factor Measurement of Boronlike $^{40}\text{Ar}^{13+}$ at the ALPHA-TRAP Experiment

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The ALPHATRAP experiment, located at the Max-Planck-Institut für Kernphysik in Heidelberg, is dedicated to the measurement of the magnetic moment ( $g$ -factor) of bound electrons of highly charged ions (HCI) up to hydrogenlike  $^{208}\text{Pb}^{81+}$ . Sub-parts-per-billion precision can be achieved in the double Penning-trap setup which consists of cryogenic 7-electrode and 5-electrode cylindrical Penning traps. The eigenfrequencies of the trapped ion's motion can be measured to ultra-high precision in the precision trap with a harmonic electrostatic potential and a highly homogenized magnetic field, while the spin-related magnetic substate of the single valence electron like 1s, 2s or  $2p_{1/2}$  for hydrogenlike, lithiumlike or boronlike ions, respectively, can be determined in the analysis trap by using the continuous Stern-Gerlach effect. By determining the bound electron's  $g$ -factor, a stringent test of bound-state Quantum Electrodynamics (BS-QED) in extreme conditions can be carried out [1, 2]. In addition, the ALPHATRAP experiment can provide access to fundamental constants, such as the fine-structure constant  $\alpha$  or the electron's atomic mass 3.

In order to deliver HCI to the ALPHATRAP Penning traps, a room-temperature beamline has been built that allows to inject ion bunches from three different ion source: the Heidelberg EBIT which is designed to produce heavy HCI up to  $^{208}\text{Pb}^{81+}$ , the room-temperature HC-EBIT which is used to produce medium-Z ions and a laser ion source which can deliver single-charged  $\text{Be}^+$  ions for an envisaged usage in sympathetic laser cooling of other HCI in the Penning trap.

The first measurement campaign of ALPHATRAP has been dedicated to the determination of the ground-state  $g$ -factor of boronlike  $^{40}\text{Ar}^{13+}$ . Using non-destructive detection techniques for the

stored ion's motion, the cyclotron as well as the Larmor frequency were determined, allowing for a parts-per-billion measurement of the  $g$ -factor. This precision exceeds the one of current calculations by two orders of magnitude. Prominent systematic effects in predecessor experiments are highly suppressed in our optimised setup. The leading systematic effect during this measurement is an axial frequency drift, caused by the slow thermalisation of the voltage source. In this contribution the status of ALPHATRAP, its results on  $^{40}\text{Ar}^{13+}$  as well as the future perspectives will be presented.

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## Precision Spectroscopy of Atomic Hydrogen and the Proton Radius Puzzle

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Precise determination of transition frequencies of simple atomic systems are required for a number of fundamental applications such as tests of quantum electrodynamics (QED), the determination of fundamental constants and nuclear charge radii. The sharpest transition in atomic hydrogen occurs between the metastable 2S state and the 1S ground state with a natural line width of only 1.3 Hz. Its transition frequency has been measured with almost 15 digits accuracy using an optical frequency comb and a cesium atomic clock as a reference 1. A measurement of the Lamb shift in muonic hydrogen is in significant contradiction to the hydrogen data if QED calculations are assumed to be correct 2. In order to shed light on this discrepancy the transition frequency of one of the broader lines in atomic hydrogen has to be measured with very good accuracy. For this purpose we have employed our previous 1S-2S apparatus as a cold source of laser excited 2S atoms in order to perform spectroscopy on the 2S-4P transitions. With a natural line width of 12.7 MHz, large Doppler effects, quantum interference etc. a good line shape analysis is mandatory to identify the true transition frequency. Our result on this transition yields a value for the proton radius that is compatible with the value obtained from muonic hydrogen with an uncertainty that is comparable to the previous hydrogen world data 3. Meanwhile Helene Fleurbaey and her team at the Laboratoire Kastler Brossel, Paris have re-measured the 1S-3S transition frequency with a significantly improved accuracy and find the previous “regular hydrogen charge radius” [4]. At our lab we have also been working on this transition with a different method. We hope to be ready to report a result soon. This will provide a unique opportunity to compare two highly accurate measurements obtained at different labs. References

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## Antimatter under the Microscope: High-Precision Comparisons of the Fundamental Properties of Antiprotons and Protons

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According to the Standard Model of particle physics - the condensate of human knowledge about the clockwork of nature - the Big Bang has produced equal amounts of matter and antimatter. On the other hand, cosmological observations imply that the visible part of the universe is entirely made out of matter. This striking inconsistency, one of the hottest topics of modern physics, inspires experiments to compare the fundamental properties of matter-antimatter conjugates at lowest energy and with great precision. The BASE collaboration at the CERN antiproton decelerator is performing such high-precision comparisons with protons and antiprotons. Using advanced, ultra-stable, cryogenic particle traps and superconducting detectors with single particle sensitivity, we have performed the most precise measurement of the proton-to-antiproton charge-to-mass ratio with a fractional precision of 11 significant digits <sup>1</sup>. In another measurement, we have invented a novel spectroscopy method, which allowed for the first ultra-high precision measurement of the antiproton magnetic moment with a fractional precision of 1.5 parts in a billion <sup>2</sup>. Together with our recent measurement of the proton magnetic moment <sup>3</sup> this improves the precision of previous experiments [4] by more than a factor of 3000.

In my talk I will review the recent achievements of BASE and will outline strategies to further improve our high-precision studies of matter-antimatter symmetry. In future studies we will profit from the high sampling rate of our experiments and will apply time base methods, to investigate our antimatter datasets for time dependent phenomena imposed by physics beyond the Standard Model.

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## Laser spectroscopy of tin across N=82

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High-resolution collinear laser spectroscopy has been performed on a long sequence of tin ( $Z=50$ ) species, spanning from  $N=58$  to the very neutron-rich isotopes beyond the  $N=82$  shell closure. Hyperfine structures and isotope shifts in two atomic transitions have been measured for 38 nuclei including 11 isomers using the COLLAPS instrumentation at ISOLDE, CERN. The long-lived isomers in  $^{113,123,128}\text{Sn}$  and the ground state of  $^{133}\text{Sn}$  and  $^{134}\text{Sn}$  have been characterized for the first time. The electromagnetic moments and charge radii, determined with higher precision than former measurements, show regularities that will be discussed in the framework of nuclear structure with emphasis on two issues of key importance, the persistence of nuclear shell closures away from stability, and the emergence of “simple structure in complex nuclei”.

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## Status report of the TRIGA-TRAP experiment

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High-precision experimental data of ground-state properties of exotic nuclei allow testing the reliability of nuclear mass models. The TRIGA-TRAP experiment is a double Penning-trap mass spectrometer used to perform high-precision mass measurements of long-lived transuranium isotopes and short-lived fission-products at the research reactor TRIGA Mainz. Prompted by a recent recharge of the superconducting magnet, the magnetic field has been mapped in detail, a new drift electrode section has been installed, and the whole setup was aligned and optimized with the help of a position-sensitive ion detector. First measurements with  $^{197}\text{Au}^+$  and carbon clusters were performed to investigate the performance and the magnitude of systematic effects. The current status and the latest results will be presented.

## Development of medium-resolution in-gas-jet laser ionization spectroscopy and its application in a study of the $^{229}\text{Th}$ isomer.

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The In-Gas Laser Ionization and Spectroscopy (IGLIS) setup, operational at KU Leuven in an off-line configuration, provides means to characterize and optimize the in-gas-jet technique, which has proven its working principle in a study on the actinium isotopes [1,2], and to embark on new applications. Results from recent studies, focusing mainly on the high- to medium-resolution laser spectroscopy operation, will be presented. These include the characterization of newly designed high-Mach number 'de Laval' nozzles and a study on the reliability of wavelength meters. Future applications include a project with focusing on  $^{229}\text{mTh}$  [3,4]. The goal will be to verify the hyperfine parameters of this isomer in its, until now suspiciously absent, singly-charged state, and, more importantly, to produce a pure isomeric beam of  $^{229}\text{mTh}^{2+}$ . To achieve isomer selectivity, high resolution and fast laser hyperfine spectroscopy on  $^{229}\text{Th}^{1+}$ , the IGLIS technique is further refined to the demands of the isomer. This includes the construction of a new fast gas cell that will be loaded with tailored U-233 sources, producing the isomer via  $\alpha$  decay, along with a redevelopment of the detection part of the IGLIS setup.

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- 3 L. von der Wense et al., Nature 533 (2016),
- [4] J. Thielking et al. Nature 556 (2018),

## Search for Octupole Deformed Actinium Isotopes using Resonance Ionization Spectroscopy

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In-source resonance ionization spectroscopy of the neutron-rich actinium isotopes  $^{225-229}\text{Ac}$  has been performed at the ISAC facility in TRIUMF, probing the  $^2D_{3/2} \rightarrow ^4P_{5/2}$  atomic transition. New data on the magnetic dipole moments and changes in mean-square charge radii  $\delta\langle r^2 \rangle$  of  $^{226,228,229}\text{Ac}$  have been obtained. The comparison of the measured centers of gravity and magnetic dipole coupling constants  $a(^4P_{5/2})$  of  $^{225,227}\text{Ac}$  with a high-resolution data set is used to identify systematic uncertainties on the deduced  $\delta\langle r^2 \rangle^{A,215}$  and magnetic dipole moment values. The charge radii odd-even staggering is evaluated for the odd- $N$  isotopes, showing that  $^{226}\text{Ac}$  has an inverted odd-even staggering that might be linked with reflection-asymmetric shapes.  $^{228}\text{Ac}$  displays within experimental uncertainties no staggering behaviour. Comparison of the magnetic dipole moments of the different isotopes with Nilsson-model estimates supports this interpretation. The changes in mean-square charge radii are compared to mean-field calculations using different interactions i.a. self-consistent calculations of odd-odd nuclei breaking both parity and time-reversal symmetry assumptions.

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## High-precision mass measurements and production of neutron-deficient isotopes using heavy-ion beams at IGISOL

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The IGISOL method utilizes a gas-filled ion guide for production and capture of radioactive isotopes. The ion guide system has proven itself to be a valuable tool in producing a great variety of rare isotope beams that cover a large portion of the nuclear chart. Most often a primary beam of light ions is used together with a target foil mounted in direct contact with the buffer gas. While providing improved cooling and larger capture efficiency, direct contact also necessitates the use of light-ion primary beams in order to limit the amount of charge created within the buffer gas volume due to the passage of the primary beam. In order to overcome this limitation and to access new regions of the nuclear chart, especially the neutron deficient nuclei near the  $N = Z$ , a heavy-ion ion guide (HIGISOL) has been used that separates the target from the ion guide. The HIGISOL system was originally introduced in 1. Recently, an updated version of the system has been commissioned and used in an on-line experiment for the first time to produce neutron-deficient transition metal isotopes utilizing a 222 MeV  $^{36}\text{Ar}^{8+}$  beam on a  $^{nat}\text{Ni}$  target. In this contribution the technical implementation of the new system is presented together with the latest high-precision Penning trap mass measurements of the produced transition metal isotopes 2.

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2 M. Vilén, A. Kankainen, et al. To be submitted.

## Resonance Ionization Spectroscopy of Tungsten Using Laser Ablation and Hot Cavity Ion Sources to Determine the First Ionization Potential

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The production of ion beams of refractory elements is challenging due to their high melting points and unfavorable adsorption characteristics preventing atomization. Laser ablation is a possibility to overcome these problems and evaporate these elements efficiently and produce a reasonable density of atomic tungsten gas inside a laser ion source volume. The technique was tested and characterized in Mainz in combination with Resonance Ionization Spectroscopy (RIS) to study high-lying atomic energy levels in tungsten, the element with the highest melting point in the periodic table of 3422 °C. To do so a high repetition rate pulsed Nd:YAG laser as ablation laser and a Ti:sapphire laser system pumped by a commercial 532 nm Nd:YAG laser for RIS were used. New three step ionization schemes were developed exploiting strong autoionizing resonances. Additionally, Rydberg series converging to the first excited  $5d^4(^5D)6s-6D_{3/2}$  state of the tungsten ion with an energy of  $1518.829(1) \text{ cm}^{-1}$  above the IP 1 were explored. The experimental data enabled a re-determination of the first ionization potential. A value more than  $5\sigma$  away from the current literature value of  $E_{IP} = 63427.7(8) \text{ cm}^{-1}$  was obtained. To confirm the data an independent measurement was performed at the IRIS2 mass separator at ORNL 3 using a hot cavity laser ion source made of tungsten. There, Rydberg series to the first excited state of the ion and additionally to the Rydberg-series converging to the  $5d^46s-6D_{1/2}$  ionic ground state were identified. Both results agree with each other and thus a correction of the literature value is required. The experimental results of this studies in the ablation source and in the hot cavity source are presented. Further applications of the laser ablation - RIS combination to other refractory elements and the optimization of the process parameter regarding high efficiency and purity of the ion beam are in preparation.

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3 Liu Y 2014: ORNL developments in laser ion sources for radioactive ion beam production; Hyper-fine Interact 227 85-99

## Double-trap Measurement of the Proton Magnetic Moment at 0.3 Parts Per Billion Precision

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Precise measurements of the fundamental properties of the proton such as its mass, lifetime, charge radius, and magnetic moment are important for our understanding of the physics of atomic and nuclear structure as well as for tests of fundamental symmetries. As one of very few particle-antiparticle pairs which are directly comparable, the proton and antiproton serve as an important laboratory for tests of charge parity time-reversal (CPT) symmetry and the weak equivalence principle.

In this poster we present our latest direct measurement of the proton magnetic moment with a relative precision of  $3 \times 10^{-10}$  1. This improves our previous measurement by a factor of 11 2 and is 33 times more precise than measurements based on the hydrogen MASER. A comparison with our recent measurement of the antiproton magnetic moment 3 constitutes one of the most precise tests of the CPT symmetry in the baryon sector.

The advancement was achieved by the application of an improved double Penning-trap technique. An optimized Penning-trap geometry with a more homogeneous magnetic field in the measurement trap and the application of a self-shielding coil allowed stabilization of magnetic field (cyclotron frequency) fluctuations by an order of magnitude. Together with a carefully optimised spin-flip drive, this led to a significantly reduced line width of the  $g$ -factor resonance. An improved superconducting cyclotron resonator increased the cooling rate by a factor of 4, thereby cutting measurement times in half and increasing statistics accordingly.

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2 Mooser, A. et al. Direct high-precision measurement of the magnetic moment of the proton. *Nature* 509, 596 (2014)

3 Smorra, C. et al. A parts-per-billion measurement of the antiproton magnetic moment. *Nature* 550, 371 (2017)

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## Recent developments at the ISOLDE RILIS

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The characteristic high efficiency and selectivity of resonance ionisation led to the implementation and development of laser ion sources at thick-target ISOL facilities 1. Located at the ISOLDE-CERN radioactive beam facility, the Resonance Ionisation Laser Ion Source (RILIS) 2 is the most frequently used ion source and has delivered the majority of beams to users in recent years. To satisfy the continued demand for laser-ionised beams, a sustained programme of consolidation and upgrades to the existing infrastructure has taken place allowing several thousand hours of operation to be delivered year on year 2.

In addition to this, research and development to extend the capabilities of various aspects of the RILIS is ongoing. Significant progress has been made in constructing and commissioning narrow-linewidth laser systems for future applications such as high-resolution spectroscopy utilising two-photon transitions or perpendicular illumination in a LIST 3. The extraction of laser ions from the VADLIS was improved boosting the efficacy of the RILIS mode of operation for this ion source [4]. Additionally, an investigation into the use of picosecond lasers for molecular fragmentation inside the ion source has begun. An overview of the planned activities for CERN's Long Shutdown 2 will be given including the development of a new beam stabilisation and observation system to enable parallel dual-separator RILIS operation.

1 V. Fedosseev et al., J. Phys. G: Nucl. Part. Phys. 44 084006 (2017)

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## Study the Standard Model with Precision

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The Standard Model is the results of many observations in ,e.g., atomic, nuclear and high energy physics. Its strength is in the wide range of predictions which can be subject to experimental verification or even falsification. Today we have reached an era where achievable precision, in experiments as well as in Standard Model calculations, has become one of the most promising routes to find answers to open questions, such as the nature of discrete symmetry violations or matter-antimatter asymmetries.

The tutorial will discuss a few possible experimental approaches.

These exploit the precision achievable in atomic physics experiments and are executed with ions, atoms or molecules. We will focus on precision experiments aiming at the measurement of discrete symmetry violations. An example is the determination of the strength of the parity violating weak interaction in atomic systems. In particular we will discuss the possibility to determine the strength at low momentum transfer by laser spectroscopy of a single trapped ion. We will center the discussion on questions like: Why is such a system suitable for high precision? What will be the observable? Can we estimate the attainable precision? What can be learned from such a measurement?

Another example is the search for a CP-violating permanent electric dipole moment (EDM) of a fundamental particle. The observation of a nonzero EDM at the present experimental sensitivity provides unambiguous evidence for physics beyond the Standard Model and could give a hint towards the understanding of the observed matter-antimatter asymmetry in the universe. Worldwide many experiments are currently underway. They are executed on particles, atoms, molecules, ions,

liquids and solids. Again we are confronted with the same questions. What makes a particular experimental approach attractive? We are aiming at discussing strategies which might help us to find an answer.

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## Towards Antihydrogen in a two-frequency Paul trap

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We present a novel experimental approach to produce and trap Hydrogen, with a long-term planning for cold Anti-Hydrogen production. We envision trapping protons and electrons by employing a Paul trap which is operated with two different drive frequencies 1. We present the status of the setup, including a chip-based microwave guide for electrons, which is extending a previous design 2 by additional segmented electrodes for axial confinement. As both electrons and protons do not allow for direct laser cooling, we inject protons with an ion gun to study sympathetic cooling using large crystals of laser cooled Be<sup>+</sup>-ions, in a similar fashion as the GBAR experiment at CERN which is aiming to sympathetically cool Anti-Hydrogen ions 3. A novel segmented chip-based trap has been set up which features transparent electrodes to observe the fluorescence of trapped Be<sup>+</sup>-ions as well as an angled trap axis to help separating the ion beam from the cooling laser.

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2 J. Hoffrogge et al., “Microwave Guiding of Electrons on a Chip”, *PRL* 106, 193001 (2011)

3 P. Pérez et al., “The GBAR antimatter gravity experiment”, *Hyperfine Interactions* 233, 21-27 (2015)

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## Laser cooling of stored relativistic heavy ions

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Storing and cooling of ions offers great possibilities for high-precision spectroscopy studies. Cooled ions have a well-defined velocity with a small spread and can, owing to the often ideal vacuum conditions, be interrogated for longer periods of time. Laser cooling is a very powerful and frequently used method to obtain very cold ions in traps. However, this is mostly true for light ions in low charge states and at low velocities. At heavy-ion storage rings, such as the ESR at GSI (Darmstadt, Germany) and the CSRe at the IMP (Lanzhou, China), we address the opposite sides of these cases, *i.e.* heavy ions in high charge states and at high velocities. Laser cooling is then not used to slow down the particles to rest, but to reduce their longitudinal temperature (velocity spread) at a fixed velocity, which is close to the speed of light. In this research field, accelerator physics meets atomic physics and laser physics. The relativistic velocities of the ions are being exploited to use *cooling transitions* which are otherwise not accessible. Due to the huge Doppler shift of the laser light, as seen by the ions when they propagate anti-collinearly to the laser photons, *normal* laser wavelengths (UV/VIS) can be used to assess XUV-transitions (fine structure!) inside highly-charged ions. We use state-of-the-art laser and detector systems, which are especially developed or tailored for storage ring experiments. The laser systems should have enough power and a very high repetition rate (~MHz). The detector systems should have good sensitivity and good photon collection and detection efficiencies. We will express our interest in highly-charged ions, discuss the ingredients for laser cooling at storage rings, show some important and new results, and finally present our future plans (SPARC@FAIR).

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## High accuracy calculations of electron affinity of astatine

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The electron affinity of astatine was calculated within the relativistic coupled cluster (CCSD(T)) approach. To obtain an estimate of the accuracy our prediction, we performed calculations for the lighter homologue, iodine. Influence of various computational parameters (number of correlated electrons, choice of the Hamiltonian, basis set, etc.) on the results was investigated. Our final values are obtained using the 4-component Dirac Hamiltonian, all electrons are correlated, and the results are extrapolated to the complete basis set limit and corrected for the Breit and QED contributions, and for the contribution of the higher excitations. The different sources of error will be discussed and an estimate of the uncertainty of the predicted electron affinity will be provided. Our results will also be compared to other earlier theoretical predictions.

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## GALS setup at JINR - production and study of heavy neutron rich nuclei

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A new setup, based on stopping nuclei in the gas cell and subsequent resonance laser ionization and separation by magnetic field is now under construction at Flerov Lab JINR. This setup aims to synthesis and study of new neutron rich heavy nuclei produced in low energy multi-nucleon transfer reactions.

The heavy neutron rich nuclei is very important for nuclear physics investigations, for the understanding of astrophysical nucleosynthesis and r-process. In this region is the closed neutron shell N=126 located which is the last so-called “waiting point”. Study of the structural properties of nuclei along the neutron shell N = 126 could also contribute to the present discussion of the quenching of shell gaps in nuclei with large neutron excess.

A creation and launch of this facility will open a new field of research in low-energy heavy-ion physics, and new horizons in the study of unexplored “north-east” area of the nuclear map. It could be helpful also for finding a new way for production heavy and superheavy nuclei.

The current status and perspectives of this setup will be discussed.

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## Mass spectrometry of Rhenium carbonyls in the gas phase

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Since the first organometallic compound of a superheavy element, Sg(CO)<sub>6</sub>, was successfully synthesized in 2013<sup>1</sup>, and the mononuclear Bh carbonyls, Bh(CO)<sub>5</sub>, is expected to be synthesized in experiment. In this study, the same B7 group Re carbonyls was investigated in the gas phase by a laser ablation based time of flight spectrometer. To produce mononuclear Re carbonyl ions in gas phase, the experimental setup was constructed as show in Figure 1(a), which includes a laser ablation cluster source and a Wiley-McLaren type time of flight spectrometer.

Figure 1 (b) shows the mass spectra in the condition of a pure Re target reacting with mixture gas H<sub>2</sub> and CO (14%) seeded in He. When very little impurity of H<sub>2</sub>, excess CO (CCO = 14%) and He as carrier gas, the mainly products Re<sup>+</sup> and [Re(CO)<sub>6</sub>]<sup>+</sup> ions can be observed clearly in the mass spectrum. While neither intermediates nor other products can be observed. When adding 14% of H<sub>2</sub> into the carrier gas, only few [Re(CO)<sub>5</sub>·(H<sub>2</sub>)]<sup>+</sup> can be observed and no other Re carbonyl hydrides appear when CH<sub>2</sub> is lower than 5%. Therefore, the impurity of H<sub>2</sub> has no great influence on the formation of [Re(CO)<sub>n</sub>]<sup>+</sup>. When adding H<sub>2</sub> and O<sub>2</sub> into the CO and He carrier gas (CCO was fixed at 14%; CH<sub>2</sub> and CO<sub>2</sub> varied from 14% to 0.002%) as show in figure 1 (c). There have several stable

Re carbonyl hydroxyls and oxides products like  $[\text{ReO}_2 \cdot (\text{OH})_2]^+$  and  $[\text{ReO} \cdot (\text{CO})_5]^+$  can be observed. The only significant reaction-products are  $[\text{ReO}_2 \cdot (\text{CO})_4]^+$  and  $[\text{Re}(\text{CO})_6]^+$ .  $[\text{ReO}_2 \cdot (\text{CO})_4]^+$  disappears completely when  $\text{CO}_2$  is 0.002%. As a result, we conclude that the impurity  $\text{H}_2$  is not sensitive to produce Re carbonyls, but even very less impurity  $\text{O}_2$  plays a great role in the formation of Re carbonyls.

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Figure 1. (a) the schematic diagram of the experimental apparatus; (b) the mass spectra in the conditions of only varied  $\text{H}_2$  impurity ( $\text{CH}_2$  1.5 -14%) and fixed  $\text{CO}$  (14%) mixture gases; (c) the mass spectra in the condition of  $\text{H}_2$  and  $\text{O}_2$  impurities in  $\text{CO}$  and  $\text{He}$  gas mixture ( $\text{CCO}$  is 14%, while  $\text{CH}_2$  and  $\text{CO}_2$  vary from 14% to 0.002% in the same steps).

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