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## **Book of Abstracts**



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## Laser Spectroscopy of $^{208}\text{Bi}^{82+}$ at the Experimental Storage Ring ESR

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Laser spectroscopy of highly charged ions at the Experimental Storage Ring (ESR) at GSI has a long tradition and started in 1994 with the observation of the hyperfine transition in  $^{209}\text{Bi}^{82+}$  [1]. While carried out to test QED in the strongest magnetic fields available in the laboratory, it turned out that uncertainties in the nuclear structure contributions, specifically the nuclear magnetic moment distribution (Bohr-Weisskopf effect), completely cover the QED contributions. In order to escape this problem, it was suggested to combine the measurement in H-like Bi with a corresponding measurement in the Li-like ion to remove the nuclear contributions in a specific difference  $\Delta'E$  of the two hyperfine splitting energies [2]. The first precise determination of  $\Delta'E$  revealed a more than  $7\sigma$  deviation between experiment and theory [3]. This could be resolved by an NMR redetermination of the nuclear magnetic moment of  $^{209}\text{Bi}$  [4], which is the only experimental input parameter into the calculation of  $\Delta'E$  and brought theory and experiment to agreement. In order to demonstrate the elimination of the BW effect in the specific difference, a measurement of  $\Delta'E$  for the isotope  $^{208}\text{Bi}$  has been proposed [5]. Here, I will present the first step of this endeavour, which was the successful measurement of the hyperfine splitting in  $^{208}\text{Bi}$  by the LIBELLE cooperation, which represents the very first laser spectroscopy of an artificially produced isotope at a storage ring.

[1]: I. Klaft *et al.*, Phys. Rev. Lett. **73**, 2425 (1994).

[2]: V. M. Shabaev, *et al.*, Phys. Rev. Lett. **86**, 3959 (2001).

[3]: J. Ullmann *et al.*, Nat. Comm., **8**, 15484 (2017).

[4]: L. Skripnikov *et al.*, Phys. Rev. Lett. **120**, 093001 (2018).

[5]: S. Schmidt, *et al.*, Phys. Lett. B **779**, 324 (2018).

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## Two-body currents in magnetic dipole moments based on nuclear DFT

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The electromagnetic (EM) moments and transitions in atomic nuclei provide fundamental insights into the nuclear structure and great progress has been achieved in past decades. However, the experimental deviation on EM moments and the 50-year-old quenching puzzle of beta decays indicate the impact of many-body contributions to the EM structure is non-negligible.

In recent years, the ab-initio calculations have explored the EM observables and weak transitions with contributions beyond the standard one-body operators. In Ref. [1], it is proposed that the missing nuclear correlations and the neglected contributions from meson-exchange currents are possible causes of the quenching phenomenon in beta decays.

More recently, Refs. [2, 3] focused on the magnetic moments from deuteron up to bismuth, including both manybody correlations and the leading EM two-body currents (2BC). On the other hand, the nuclear DFT can provide a global description of nuclear electric quadrupole and magnetic dipole moments, for example in one-particle and one-hole neighbors of doubly magic nuclei [4] or in open shell nuclei [5]. In our presentation, we introduce the first implementation of 2BC based on nuclear DFT in Jyväskylä-York collaboration to explore the contribution of higher-order current operators to magnetic dipole moments. The implementation is based on a use of auxiliary spherical harmonic oscillator basis, on which the two-body magnetic operator matrix elements are calculated. With use of unitary transformation, we can then compute the contribution of two-body currents on the magnetic moment for angular-momentum projected, deformed open shell nuclei. Further calculations are currently in progress.

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[2] R. Seutin et al., *Phys. Rev. C* 108, 054005 (2023).

[3] T. Miyagi et al., arXiv 2311, 14383 (2023).

[4] P. Sassarini et al., *J. Phys. G Nucl. Part. Phys.* 49, 11LT01 (2022).

[5] J. Bonnard et al., *Phys. Lett. B* 843, 138014 (2023)

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## High-precision laser spectroscopy of helium-like carbon

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The nuclear charge radius is a key observable in nuclear structure studies. Using the Collinear Apparatus for Laser Spectroscopy and Applied Physics (COALA) at the Institute of Nuclear Physics of TU Darmstadt, an all-optical approach for the nuclear charge radius determination was tested with the well-known nucleus of  $^{12}\text{C}$ . Here, the nuclear charge radius of  $^{12}\text{C}$  was extracted purely from laser spectroscopy measurements that were combined with non-relativistic QED calculations. Laser excitation of helium-like  $^{12}\text{C}^{4+}$  started from the metastable  $2^3S_1$  state with a lifetime of 21 ms to reach the  $2^3P_J$  states. The precision of the corresponding transition frequencies was improved by more than 3 orders of magnitude. Furthermore, this work represents the starting point for the necessary improvement of charge radii of the light-mass nuclei and it will be the corner stone for investigations of the carbon isotope chain. This contribution will give an overview of the project, present the measured transition frequencies along with the extracted all-optical nuclear charge radius of  $^{12}\text{C}$  and give an outlook on upcoming measurements. This project was supported by DFG (Project-ID 279384907 - SFB 1245) and by BMBF (05P21RDFN1).

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## Nuclear structure of Pd isotopes via optical spectroscopy

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High-resolution laser spectroscopy is a powerful tool to extract nuclear structure data in a nuclear-model-independent manner. The isotope shift gives direct access to changes in mean-square charge radii, while the extracted hyperfine parameters give access to the nuclear spin, magnetic dipole and electric quadrupole moment. All this provides information on e.g. deformation, shape coexistence and shell structure. Recently, measurements of ground state properties have also proven exceptionally potent in testing state-of-the-art nuclear theory.

The Pd isotopes are located in a transitional area between chains which display smooth trends in the charge radii (Sn region), and a region where the charge radii and electric quadrupole moments show evidence of a shape change at N=60, centred around yttrium. Between both however, i.e. Tc, Ru, Rh and Pd, no optical spectroscopic information has been available for radioactive nuclei so far. This is partly due to the refractory character of these elements, making production challenging for many facilities, but also their complex atomic structure.

At the IGISOL facility, these difficulties were overcome thanks to the chemically insensitive production method, and the installation of a charge-exchange cell. Collinear laser spectroscopy was performed on unstable Pd isotopes, known to be deformed from decay spectroscopy studies, although there is disagreement on the (possible) change in deformation. The measured nuclear charge radii, spins and electromagnetic moments [1,2] will be presented in this contribution, and the implication on the deformation will be discussed. Additionally, the results will be compared to Density Functional Theory (DFT) calculations using Fayans functionals. As most recent benchmarks of nuclear DFT were performed on spherical systems, close to (doubly-)magic systems, this presents a stringent test of the Fayans functionals for well-deformed isotopes.

[1] S. Geldhof et al., Phys. Rev. Lett. 128, 152501 (2022).

[2] A. Ortiz-Cortes, PhD thesis, University of Jyväskylä and Normandy University (2023).

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## Latest results from LEBIT and upgrades to the stopped beam facilities at FRIB

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The Low-Energy Beam and Ion Trap (LEBIT) facility [1] at the recently commissioned Facility for Rare Isotope Beams (FRIB) remains the only facility that employs Penning trap mass spectrometry for high-precision mass measurements of rare isotopes produced via projectile fragmentation. This powerful combination of a fast, chemically insensitive rare isotope production method with a high-precision Penning trap mass spectrometer has yielded mass measurements of short-lived rare isotopes with precisions below 10 ppb across the chart of nuclides. The first LEBIT measurement campaigns in the FRIB era were a mass measurement of the proton dripline nucleus <sup>22</sup>Al [2], a potential proton halo candidate, as well as providing an isomerically purified beam of <sup>70</sup>Cu to the SuN total absorption spectrometer that was installed downstream of LEBIT.

To expand the experimental reach of Penning trap mass spectrometry to nuclides delivered at very low rates, the new Single Ion Penning Trap [3,4] (SIPT) has been built. SIPT uses narrowband FT-ICR detection under cryogenic conditions to perform mass measurements of high-impact candidates, delivered at rates as low as one ion per day, with only a single detected ion. Additional upgrades to the stopped beam facility at FRIB, including a high-resolution magnetic mass separator and high-performance MR-ToF will ensure that the mass measurement program will make optimal use of the wide range of rare isotope beams provided by FRIB.

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[4] S. Campbell et al., *Atoms* 11, 10 (2023).

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## Shape Coexistence Near Doubly-Magic <sup>78</sup>Ni

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Investigating nuclear structure, especially nuclear shells and their associated magic numbers, has been an important field of research in the last decades. Such proton and neutron numbers are associated with sudden changes in nuclear observables between neighboring isotopes, such as binding energies, charge radii, transition strengths, etc. With  $N = 50$  neutrons and  $Z = 28$  protons, the <sup>78</sup>Ni nucleus at the crossroads at two magic numbers is a prime candidate to test our understanding of the shell model [1]. Furthermore, the effect of shape coexistence, i.e. the existence of spherical ground states and deformed excited states, is often found in nuclei where intruder states across shell gaps lead to a large amount of deformation [2], indicating nearby magicity. Indication for shape coexistence in <sup>79</sup>Zn with  $N = 49$  and  $Z = 30$  has previously been found through laser spectroscopy

experiments [3] and in  $^{80}\text{Ga}$  with  $N = 49$  and  $Z = 31$  through electron-conversion spectroscopy [4]. The latter, however, was disproven in follow-up experiments [5,6]. In this contribution, we present further evidence for shape coexistence in  $^{79}\text{Zn}$  through the first direct excitation energy measurements of the  $\frac{1}{2}^+$  isomeric state using Penning trap and multi-reflection time-of-flight mass spectrometry, firmly establishing the  $\frac{1}{2}^+$  and  $5/2^+$  state ordering [7]. Utilizing discrete nonorthogonal shell model calculations, we find low-lying deformed intruder states, similar to other  $N = 49$  isotones, and investigate similarities in shapes between excited states in  $^{79,80}\text{Zn}$  and  $^{78}\text{Ni}$ .

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- [2] Garrett, Zielińska, and Clement, *Prog. Part. Nucl. Phys.* 124, 103931 (2022)
- [3] Yang et al., *PRL* 116, 182502 (2016)
- [4] Gottardo et al., *PRL* 116, 182501 (2016)
- [5] Garcia et al., *PRL* 125, 172501 (2020)
- [6] S. Sekal et al., *Phys. Rev. C* 104, 024317 (2021).
- [7] Nies et al., *PRL* 131, 222503 (2023)

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## Recent mass measurements of neutron-rich rare-earth nuclides with the JYFLTRAP double Penning Trap at IGISOL for the astrophysical r-process

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High precision atomic mass spectrometry of neutron-rich rare-earth nuclides near  $A \sim 165$  was performed recently with the JYFLTRAP double Penning trap [1] using the phase-imaging ion cyclotron resonance technique [2] at the IGISOL facility in the JYFL Accelerator Laboratory. Altogether eighteen masses across the lanthanum, terbium, dysprosium and holmium isotopic chains were measured, including the very first direct mass measurements of  $^{152,153}\text{La}$ ,  $^{169}\text{Tb}$  and  $^{170,171}\text{Dy}$ . We continued the previous successful measurement campaigns at JYFLTRAP in this region [3,4] and now reached up to the  $N=104$  neutron midshell, important for studying how the nuclear structure evolves further from stability. The properties of these nuclides also impact the models describing the formation of the rare-earth abundance peak around  $A \sim 165$  in the astrophysical rapid neutron capture (r) process [5], which has produced around half of the heavy-element abundances in the Solar System and takes place at least in neutron-star mergers. As variations in nuclear masses affect all the relevant nuclear properties of neighboring nuclei that depend on the mass, reducing their related uncertainties give better constraints on the calculated astrophysical reaction rates. The results are thus critical inputs for modelling the stellar nucleosynthesis and for understanding origins of different chemical elements and their abundances in the Solar System.

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- [3] M. Vilen et al., *Physical Review Letters* 120, 262701 (2018)
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- [5] M. Mumpower et al. *Physical Review C* 85, 045801 (2012)

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## Pushing the Limits of Ab-Initio Theory through Precision Mass Measurements of Neutron Rich Potassium at TITAN

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TRIUMF's Ion Trap for Atomic and Nuclear science (TITAN) is a set of connected ion traps for rare isotope science. TITAN operates a Multi-Reflection Time-Of-Flight Mass Spectrometer (MR-TOF-MS) primarily for nuclear mass measurements and isomerically selective ion beam cleaning. TITAN's MR-TOF-MS has demonstrated excellent dynamic range ( $\sim 10^8$ ), high-precision ( $\frac{\delta m}{m} \sim 10^{-7}$ ) and high-speed ( $\sim 5$  ms) mass measurements, allowing for the study of very exotic isotopes. Additionally, TITAN has developed new techniques enabling the measurement of half-lives using the MR-TOF-MS. This has allowed for half-life measurements of isotopes between  $\sim 5$  ms and  $\sim 5$  min. Concurrent decay detection with mass measurements as been developed as a routine tool for supplementary identification of rare isotope species at TITAN. TITAN's MR-TOF-MS's unique ability to self-purify ion beam through mass selective re-trapping has made this a particularly powerful technique for science at TITAN. Applications of these new techniques for the study of nuclear structure and nucleosynthesis will also be discussed.

TITAN has recently used the MR-TOF-MS to make a set of mass measurements clarifying the nuclear structure near  $N=34$  in potassium. Experimental ground state masses are compared to new state of the art ab-initio calculations. This is used to benchmark the accuracy of novel nuclear interaction models near the neutron dripline.

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## Progress towards atomic parity violation measurements in francium

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Low-energy precision tests of electro-weak physics keep playing an essential role in the search for new physics beyond the Standard Model. Atomic parity violation (APV) experiments measure the strength of highly forbidden atomic transitions induced by the exchange of Z bosons between electrons and quarks in heavy atoms. APV is sensitive to additional interactions such as leptoquarks, and provides complementary sensitivity to parity-violating electron scattering. Our group is working towards a measurement in francium, the heaviest alkali, where the APV signal is about 18 times larger than in cesium. Since Fr has no stable isotopes, we have established an online laser trap at the ISAC radioactive beam facility at TRIUMF that can confine millions of cold francium atoms at micro-Kelvin temperatures in a volume of approximately 1 cubic mm, an ideal environment for precision spectroscopy. Recently, we have observed the highly forbidden 7s-8s magnetic dipole transition, a final milestone prior to observing APV. I will review our recent work and present a roadmap for APV.

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## Parity-Violating Nuclear Effects From Single Molecules In A Penning Trap

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This contribution will introduce a new experiment at MIT in which ion trapping and laser spectroscopy techniques are combined for precision measurements of fundamental symmetries and yet-to-be-explored nuclear electroweak properties [arXiv:2310.11192]. In particular, single trapped molecular ions can amplify the sensitivity to nuclear-spin-dependent parity-violating effects, such as the nuclear anapole moment, by more than 12 orders of magnitude compared to atoms. The current status and prospects for studying radioactive molecules will be discussed.

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## Measurement of Analog-Antianalog Isospin Mixing in <sup>47</sup>K Beta Decay

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While both Charge-Parity (CP) symmetry, and more recently Time (T) symmetry have been directly shown to be violated in the weak interaction, it remains an open question whether new sources of CP violation could explain the matter-antimatter asymmetry in the universe. TRIUMF's Neutral Atom Trap (TRINAT) is equipped to study the angular distribution of all decay products from spin-polarized beta emitting isotopes produced by the Isotope Separator and Accelerator (ISAC) facility. Decay from <sup>47</sup>K (I=1/2) into the isobaric analog state is energetically forbidden, but instead 80% of the decays proceed via an isospin changing branch to a single I=1/2 state. The recoil asymmetry is made nonzero by the product of the Gamow-Teller and isospin-suppressed Fermi matrix elements, an effect we measured at TRINAT in order to test analog-antianalog isospin mixing.

We discuss the experiment and resulting magnitude of the Coulomb mixing of the candidate antilog  $1/2^+$  final state with the unbound isobaric analog resonance of  $^{47}\text{gK}$ . Our measurement was carried out by trapping approximately  $10^3$  laser-polarized  $^{47}\text{K}$  ( $t_{1/2} = 17.5 \pm 0.24$  s) atoms at a time over the course of approximately one day.

A future measurement of  $DI \cdot v_\beta \times v_\nu$  would have enhanced sensitivity to isospin-breaking, parity even, T-odd interactions, since they would be referenced to the Coulomb interaction. Furthermore, constraints from the neutron EDM on D [Ng, Tulin PRD 2012] are relaxed for such isospin-breaking interactions.

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## Current status of MORA at IGISOL

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Around us we see an universe filled with galaxies, stars and planets like ours. But when we look back to the Big Bang and the processes that created the matter in it, at first we observe that there should have been created the same amount of matter and antimatter, thus the universe would be empty or different than it is. Sakharov suggested several conditions to explain the matter-antimatter asymmetry, one of them being the violation of the CP symmetry.

In the MORA experiment, we aim to measure the D correlation, which is non zero for violation of T symmetry in polarized nuclei, thus it can be related to CPV. For this we use a detector setup made of MCP's, Phoswiches and Si detectors, to measure coincidences between beta emissions and recoil ions, product of the beta decay of trapped  $^{23}\text{Mg}$  ions.

Here I will present an introduction to D correlation, how we acquired the latest data in JYFL, how we analyzed it and the results we got concerning the calibration of detectors and polarization measurement.

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## Present status and future prospects of SCRIT electron scattering facility

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The world's first electron scattering off online-produced Radioisotope (RI) was successfully conducted at the SCRIT (Self-Confining RI Ion Target) electron scattering facility in RIKEN RI Beam Factory in Japan.

Electron scattering stands out as one of the most potent and reliable tools for investigating the



structure of atomic nuclei, owing to the well-understood mechanism of electromagnetic interaction.

Despite a long-standing desire to explore exotic features of short-lived unstable nuclei through electron scattering, it has been impeded by the difficulty in preparing thick targets.

We have recently achieved a significant milestone by realizing electron scattering from  $^{137}\text{Cs}$ , which was generated via the photo-fission of uranium and promptly transferred to the SCRIT system for trapping within a short time.

The SCRIT is a novel internal target-forming technique, which allows us to form a stationary target along the electron beam and achieve high luminosity with a small number of target ions.

This experiment serves as a noteworthy emulation of electron scattering from short-lived unstable nuclei produced online, such as  $^{132}\text{Sn}$  in the future.

In this contribution, we will present recent progress and prospects of the SCRIT electron scattering facility.

Additionally, we will discuss several topics that may only be feasible in the future using the SCRIT method.

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## Noble Gas measurements of nuclear fuel particles from Chernobyl

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During the Chernobyl reactor accident on April 26, 1986, radioactivity was in part released in the form of nuclear fuel particles. These so-called “hot particles” have various structures that belong to specific oxidation states of uranium. These oxidation states behave differently in the environment. We obtain individual particles by density separation with a poly tungsten solution. Via radiometric scanning with a Geiger counter we locate the particles. The extraction is performed on tungsten needles with a micromanipulator in a scanning electron microscope (SEM).

The particle surface was analyzed by different nondestructive methods such as SIMS, rL-SNMS and EDX. Gamma measurements and optical analyses in SEM were also performed. The particles are then heated to over 1000°C using a laser beam. This releases the noble gases Kr and Xe from the particles, which can be analyzed using a static mass spectrometer. The age and the neutron flux that the particle has experienced in the reactor can be determined individually for each particle.

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## Development of mid-infrared cavity ring-down spectrometers for radiocarbon/tritium analysis in biomedical tracer and environmental applications

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The long-lived radioactive carbon isotope  $^{14}\text{C}$  is widely used as a tracer in environmental and biomedical studies. We have developed a  $^{14}\text{C}$  analytical system based on highly sensitive cavity-enhanced laser absorption spectroscopy, i.e., cavity ring-down spectroscopy (CRDS), and demonstrated  $^{14}\text{C}$  tracer analysis in pharmacokinetics and other areas. In parallel with the development of the  $^{14}\text{C}$ -CRDS, we are focusing on the development of a mid-infrared cavity ring-down spectrometer for tritium analysis. Combined with a robust injection system for small water samples, the analytical performance of the system was investigated using deuterium water analysis. This presentation will overview the CRDS-based  $^{14}\text{C}$  and  $^3\text{H}$  analytical systems and recent results.

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## Elemental ratios of spent nuclear fuel by resonance ionization mass spectrometry

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In recent years resonance ionization mass spectrometry (RIMS) has shown great progress in analyzing individual micrometer-sized samples. Selective laser ionization of elements resolves most of the abundant isobaric interferences in complex matrices, like spent nuclear fuel. In RIMS, laser light is aimed at a neutral atomic cloud sputtered from the sample surface by a pulsed primary ion source comparable to those found on a commercial static ToF-SIMS instrument. This enables an ultra-trace level analysis free of isobaric interferences with minimal sample consumption.

However, analyses thus far have been limited to measuring isotopic ratios within one element. Ratios of isotopes between elements have been challenging as each element is ionized by separate lasers. Recent improvements to the measurement routine on the Laser Ionization of Neutrals (LION) instrument at the Lawrence Livermore National Laboratory (LLNL, USA) now allows the study of interelemental ratios.

We present the first comprehensive study of elemental ratios from spent nuclear fuel samples by RIMS. This provides increased insight into the sample's history compared to isotopic ratio measurements alone. For example, the ratios of U/Pu and U/Zr allow a better fuel type determination. If the sample origin is known, elemental ratios allow for studying differences due to fuel type, burnup, and sample location within the reactor in great detail. Particularly, the "edge-effect" (where fission and neutron capture are significantly enhanced at the edge of a fuel pellet relative to the center of the same pellet) can be quantified.

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## Electronic Bridge schemes in $^{229}\text{Th}$ doped LiCAF

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The thorium isotope  $^{229}\text{Th}$  has attracted a lot of interest over the past few decades. This is related to its extremely low-lying first excited state at  $\sim 8$  eV and long radiative lifetime of a few  $10^3$  s [1]. This makes  $^{229}\text{Th}$  an ideal candidate for a nuclear clock with outstanding properties promising a variety of applications [2].

Large band gap crystals such as  $\text{CaF}_2$  or  $\text{LiCaAlF}_6$  (LiCAF) hosting  $^{229}\text{Th}$  have been proposed for the operation of a solid-state nuclear clock.

Among others, these crystals are transparent at the wavelength of the clock transition and a large number of nuclei can be interrogated at the same time [3]. However, DFT simulations of such environments indicate that doping of  $^{229}\text{Th}$  leads to the formation of localized electronic states in the band gap, so-called defect states [4]. These states can be used for effective nuclear excitation via the Electronic Bridge mechanism, as we could show in the case of Th-doped  $\text{CaF}_2$  crystals [4,5].

Here, we investigate theoretically different laser-assisted Electronic Bridge schemes for  $^{229}\text{Th}$  doped LiCAF crystals and present the corresponding excitation rates. Similar to  $\text{CaF}_2$  crystals, these schemes can provide, depending on the energetic position of the defect states, orders of magnitude stronger nuclear excitation/deexcitation compared to direct photoexcitation with current laser technology. The results are discussed in conjuncture with the design of a solid-state nuclear clock.

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## Laser ionization of thorium via Rydberg states in hypersonic gas jets

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Using efficient laser ionization schemes is a key element when performing atom-at-a-time laser spectroscopy. Auto-ionizing states are often used to enhance ionization due to their higher cross sections

compared to excitation directly to the continuum. Nonetheless, for certain elements, either such structures are absent or remain undiscovered <sup>1</sup>. Alternatively, another approach involves exciting the atom to high-lying Rydberg states and subsequently inducing ionization through mechanisms like field ionization, wherein a strong electric field is applied.

We report on the laser excitation of Rydberg states in a hypersonic gas jet. The In-Gas Laser Ionization and Spectroscopy (IGLIS) technique employs a convergent-divergent (de Laval) nozzle to create a cold hypersonic gas jet. Without sacrificing efficiency, the in-gas-jet method allows for sub-GHz spectral resolution of short-lived actinides with low production rates [2]. The new generation of nozzles with a Mach number of 8.5 enables laser spectroscopy studies of actinides with spectral resolutions around 200 MHz [3].

Thorium atoms were produced via laser assisted ablation inside an argon filled gas cell and evacuated via the de Laval nozzle. Rydberg states were populated in-gas-jet via laser excitation and subsequently field ionized. The analysis of the found Rydberg states for Th I together with the search for an efficient ionization scheme for Th II allowed for the extraction of an improved value for the ionization potential of both Th I and Th II. Several auto-ionizing states above the second ionization potential were discovered which will be used to improve laser ionization efficiency for in-gas-jet laser spectroscopy studies of  $^{229m}\text{Th}^+$ . The latter is of interest for the development of a  $^{229}\text{Th}$  based nuclear clock [4].

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### Collinear laser spectroscopy of U isotopes at IGISOL

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Actinide elements present a rich spectrum of nuclear structure phenomena, and have been the focus of many research programs aimed at developing a detailed picture of this region of the nuclear chart. For example, theoretical models have predicted the emergence of pronounced reflection-asymmetric shapes moving towards more neutron-deficient isotopes<sup>1</sup>. The region also hosts two unique low-lying isomeric states,  $^{229}\text{Th}$  and  $^{235}\text{U}$ , the former of which has great potential to act as a nuclear-based metrology time standard.

Laser spectroscopic techniques act as a bridge between nuclear and atomic physics, providing access to information including the evolution of mean-square charge radii through the measurement of isotopic shifts in atomic transitions, in addition to nuclear magnetic dipole and electric quadrupole

moments obtained via the hyperfine structure[2]. In the region of the actinide elements and above, these studies are often limited by the challenges in producing the nuclei of interest.

Within the LISA(Laser Ionization and Spectroscopy of Actinides) framework, a research program aimed towards the study of the nuclear structure of light actinide elements has been implemented at the IGISOL facility, at the University of Jyväskylä. High resolution collinear laser spectroscopy on natural U isotopes has been performed on 10 transitions in the singly charged ion. New information on atomic hyperfine parameters in addition to high precision isotopic shifts has been produced. In parallel, the development of a gas-cell based production method of an isomeric beam of  $^{235}\text{U}$  has been carried out, with the final aim of performing a collinear laser spectroscopy measurement of the low lying 76-eV isomer.

This contribution presents the results of these studies, the upgrades of the light collection region and the use of ultra-short time bunches to further increase the sensitivity of the technique.

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[2]Yang,X. et al. PPNP 129 (2020): 104005.

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## Nuclear octupole shapes in Actinides with Fayans functionals

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Static octupole deformation, also called reflection asymmetric by contrast with the quadrupole deformation, displays a profound signature on the observables and systematics of the nuclear ground state [1] and are expected to manifest mostly in the heavier Actinides region of the nuclear chart. Such deformations present a non-negligible impact on the excitation spectra and nuclear properties, for example on the nuclear Schiff moment [2], thus posing important tests for theoretical nuclear structure models.

The typical Skyrme energy density functional of a nuclear density functional theory encompasses many nuclear properties, giving rise to a variety of Skyrme-based EDFs, each adjusted using experimental measurements, and of which results are then compared to nuclear data [3].

In order to further improve accuracy, Fayans EDFs have been recently developed, enriching the current-generation EDFs with the Fayans pairing term [4], and have been successfully tested on various isotopic chains via the comparison with state-of-the-art charge radii measurements [5][6][7].

Based on earlier theoretical surveys in which some Actinides clusters present significant octupole deformation [8], our work aims to both verify the expected precision of the newly-adjusted Fayans functionals and confirm their stronger octupole preponderance.

As such, we present a first-of-its-kind systematic survey of octupole deformation and associated nuclear properties computed by Fayans EDFs, of which we compared the results to recent studies on pear-shaped nuclei [9]. Moreover, these new functionals manifest promising results regarding odd-even effects, namely on radii, within isotopic chains.

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## Progress at the N=126 factory at ANL

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The N=126 factory is a new facility that uses multi-nucleon transfer reactions to create neutron-rich isotopes of the heaviest elements for studies of interest to the formation of the last abundance peak in the r-process. This region of the nuclear chart is difficult to access by standard fragmentation or spallation reactions and as a result has remained mostly unexplored. The nuclei of interest, very neutron-rich isotopes around Z=70-95, will be produced by multi-nucleon exchange of a high intensity 10 MeV/u <sup>136</sup>Xe beam on the most neutron-rich stable isotopes of heavy elements such as <sup>198</sup>Pt and <sup>238</sup>U. This reaction mechanism can transfer a large number of neutrons and create with larger than mb cross-section very neutron-rich isotopes. The reaction mechanism is a nuclear surface process and the reaction products come out at around the grazing angle which makes them very difficult to collect. The N=126 factory circumvents this difficulty by using a unique large high-intensity gas catcher, similar to the one currently in operation at CARIBU, to collect the target-like reaction products and turn them into a low-energy beam that is then mass separated with a medium resolution electromagnetic separator ( $dM/M \sim 1/1500$ ), followed by an RFQ buncher and an MR-TOF ( $dM/M \sim 1/100000$ ) system. The extracted radioactive beams are essentially pure and will be available at low-energy for mass measurements with the CPT mass spectrometer, decay study with the X-array, and eventually laser spectroscopy studies. Overall status and commissioning results for the facility, together with the planned physics program, will be presented.

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## In-gas-cell laser ionization spectroscopy of heavy refractory nuclei produced at KISS

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We have developed the KEK Isotope Separation System (KISS) 1 at RIKEN to study the nuclear structure of the nuclei in the vicinity of neutron magic number  $N = 126$  and <sup>238</sup>U from the astrophysical interest. These neutron-rich nuclei have been produced by using multinucleon transfer (MNT) reactions [2] with the combinations of the low-energy <sup>136</sup>Xe/<sup>238</sup>U beams and the production targets of W, Ir, and Pt. At the KISS facility, these MNT radioisotopes are ionized by applying in-gas-cell laser ionization technique. In the ionization process, we can perform laser ionization spectroscopy of the refractory elements with the atomic number  $Z = 70-78$  such as Hf, Ta, W, Re, Os, Ir, and Pt, which can not be performed in other facilities. Laser spectroscopy is a powerful method to effectively investigate the nuclear structure through the measured magnetic moments and isotope shifts, and the deduced changes in the mean-square charge radii and quadrupole deformation parameters.

We have performed in-gas-cell laser ionization spectroscopy of <sup>199g,199m, 200, 201</sup>Pt [3], <sup>196,197,198</sup>Ir [4], <sup>194,196</sup>Os [5], and <sup>191,192</sup>Re produced at KISS. By using multi-reflection time-of-flight mass-spectrograph, we can identify the unstable nuclei from the measured atomic masses and efficiently measure the hyperfine structure, even though for long-lived nuclei, from the counting of the number of laser ionized atoms without detecting decay radiations.

In this conference, we will report the results of laser ionization spectroscopy, and the perspective of future plan at KISS.

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## Plenary / 168

**Laser-polarised unstable nuclei at ISOLDE**

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At the VITO beamline at ISOLDE 1, we use optical pumping with tunable lasers to polarise nuclear spins of different short-lived nuclei. We then use the resulting anisotropic emission of beta radiation in a variety of fields, from nuclear structure, via material science, all the way to biology.

Combining optical pumping with beta-decay detected nuclear resonance (beta-NMR) in liquid samples has allowed us to narrow the linewidth of NMR resonances by two orders of magnitude. Thanks to this achievement we have pushed to ppm levels the accuracy of magnetic moments of short-lived isotopes 1. We now use this approach to study the distribution of nuclear magnetisation through measurements of the hyperfine anomaly [2]. Recently, we have also started a programme in decay spectroscopy of laser-polarized beams, in which we study angular correlations between emitted beta particles, gamma-radiation, and neutrons. The aim is to determine spins and parities of excited states in neutron-rich nuclei, especially beta-delayed neutron emitters relevant for the r process nucleosynthesis.

This contribution will present the VITO experimental setup, recent studies with neutron rich potassium isotopes 2,3], and the upcoming measurements of the magnetic moment of <sup>11</sup>Be [4] and of solid-state battery materials with <sup>8</sup>Li [5].

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2. M.L. Bissell et al, in preparation
3. M. Piersa-Silkowska et al., CERN-INTC-2023-026 / INTC-P-662, and M. Piersa-Silkowska et al., in preparation
4. M.L. Bissell et al, CERN-INTC-2023-014 / INTC-P-655
5. G. Rees et al., CERN-INTC-2023-078 / INTC-I-267

## Plenary / 86

**Spectroscopic opportunities for rare isotopes with the MIRACLS technique and laser cooling**

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The MIRACLS experiment at ISOLDE/CERN combines the usage of ion traps and lasers to probe exotic radioactive nuclides 1. In order to increase the sensitivity of fluorescence-based collinear

laser spectroscopy (CLS), MIRACLS traps ion bunches in a Multi-Reflection Time of Flight (MR-ToF) device. Hence, the ions are probed multiple times instead of just once. This increases the laser-ion interaction time with each revolution in the MR-ToF apparatus, while the high resolution of CLS is retained by using a high-energy MR-ToF.

A successful proof-of-principle experiment with 1.5keV beam energy showed that the MIRACLS technique is working. However, to perform high-resolution CLS a newly built high-energy MIRACLS setup is currently under commissioning, with the goal to measure the charge radii of  $^{33,34}\text{Mg}$ . These observables would deepen our understanding of the  $N = 20$  island of inversion and act as stringent benchmark for nuclear theory, in particular ab initio methods.

As part of the proof-of-principle experiment, we also performed studies of laser and sympathetic cooling in a Paul trap, normally used for buffer-gas cooling [2]. Even though this trap only has axial laser access, the time spread of  $^{24}\text{Mg}$  ions was drastically reduced by laser cooling. Moreover, we sympathetically cooled  $^{16}\text{O}$ ,  $^{39}\text{K}$  and  $^{25,26}\text{Mg}$ . Backed-up by simulations, we demonstrated the feasibility of laser cooling at radioactive ion beam facilities in a time span of a few 100ms, compatible with short-lived radionuclides.

This oral contribution will introduce the MIRACLS concept, present results from a proof-of-principle experiment, show the new experimental setup and outline the opportunities of ultra-cold radioactive isotopes via laser cooling.

1 S. Sels et al., Nucl. Instr. Meth. B, 463, 310-314 (2019)

[2] S. Sels, F.M. Maier, et al., Phys. Review Research 4, 033229 (2022)

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## Laser spectroscopy of the heaviest elements

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While nuclear shell effects are responsible for the existence of the heaviest elements, their atomic structure is strongly influenced by relativistic effects that lead to different atomic and chemical properties than their lighter homologs. Here, laser spectroscopy is a powerful tool for revealing fundamental atomic and also nuclear properties, which are reflected as subtle changes in the atomic transitions studied. The general lack of atomic information on the heavy elements, the low production rates and the relatively short half-lives make experimental investigations a challenge and require very sensitive experimental techniques.

Laser spectroscopy of heavy nobelium isotopes (No,  $Z=102$ ) produced in accelerators in atom-at-a-time quantities became accessible through the pioneering experiment with the Radiation Detected Resonance Ionization Spectroscopy (RADRES) technique coupled to the SHIP velocity filter at GSI in Darmstadt. With additional developments of the setup, the range of the method was extended to  $^{251,255}\text{No}$  and for the first time also to on-line produced fermium isotopes (Fm,  $Z=100$ ). These online experiments are complemented by off-line laser spectroscopy measurements at the RISIKO mass separator of the University of Mainz on reactor-grown heavy actinides with suitable long lifetimes. Hot cavity laser spectroscopy on radiochemically purified samples enabled the investigation of isotopes of the heavy actinides curium, californium, einsteinium and fermium. These experimental efforts are accompanied by improvements in theoretical atomic calculations, which are essential for determining the properties of the nuclear ground state from the extracted atomic observables of isotopic shifts and hyperfine structure parameters. The combination of results from different fields of research provides an insight into the special nuclear nature of the heaviest elements. The results obtained are discussed with respect to the predictions of nuclear theory and the perspectives for laser spectroscopic investigations in even heavier systems.



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## Laser Spectroscopy of Californium-253,254

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The 60-day spontaneously fissioning isotope californium-254 is the most neutron-rich known isotope of this element. Due to its anomalously long half-life, it is predicted to have a particularly high impact on the brightness of electromagnetic transients associated with neutron star mergers on the timescale of 10 to 250 days [Zhu et al., AJL 863, L23 (2018)]. Experimental information on Cf-254 is scarce, owing to limited production capabilities in the laboratory. We have performed optical spectroscopy on this and other neutron-rich isotopes in this part of the nuclear chart. For this, targets of heavy Cm isotopes were neutron-irradiated at the High Flux Isotope Reactor, Oak Ridge National Laboratory (ORNL), Oak Ridge, TN, USA, to breed transcurium isotopes including Cf-252 and Es-253,254. A chemical separation performed at ORNL's Radiochemical Engineering Development Center yielded the Es fraction, which also contained some Cf-252. This sample was shipped to

Johannes Gutenberg University Mainz (JGU), Mainz, Germany, via Florida State University (FSU), Tallahassee, FL, USA, and then sent to Institut Laue-Langevin (ILL), Grenoble, France, for a second irradiation with thermal neutrons to produce more neutron-rich isotopes including the 40-d isotope Es-255, which continuously feeds the 20-h Fm-255, as well as 18-d Cf-253 and 60-d Cf-254. Laser resonance ionization spectroscopic studies were performed at the RISIKO mass separator at JGU. In californium, the hyperfine structure of the 420 nm ground state transition in Cf-253 and the isotope shift of Cf-254 in the 417 nm and 420 nm ground-state transitions were determined with high resolution down to 140 MHz FWHM by using the Perpendicularly-Illuminated Laser Ion Source and Trap (PI-LIST). These data provide a basis for a King plot analysis of the optical spectrum of Cf-254 based on known results in lighter californium isotopes, where substantially more data are available.

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## Laser spectroscopy of fermium-255 at the RISIKO mass separator facility

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Laser spectroscopy provides information about the fundamental properties of atomic and nuclear structure of the constituents of matter. Measurements are of general importance all along the nuclear chart but are specifically thrilling for the heavy actinides and superheavy elements, where data is sparse and theoretical descriptions can be tested. For an extensive measurement campaign at the RISIKO mass separator facility at the Institute of Physics at Johannes Gutenberg University Mainz, samples of the anthropogenic isotope  $^{255}\text{Fm}$  ( $Z=100$ ) with  $10^8$  to  $10^9$  atoms each were made available. They were used for studies on the atomic level structure, ionization potential, and hyperfine structure in fermium. The samples initially originate from a  $^{254}\text{Es}$  sample that was produced at the HIFR high flux research reactor at the Oak Ridge National Laboratory, Oak Ridge (USA) by neutron breeding. The sample was subsequently re-irradiated at the Institut Laue-Langevin reactor in Grenoble (F) to produce suitable amounts of  $^{255}\text{Es}$  (half-life: 39.8 d), which decays to  $^{255}\text{Fm}$  (20.07 h) via  $\beta^-$  decay, and chemically separated after appropriate ingrowth. This presentation will focus on the atomic structure studies of  $^{255}\text{Fm}$ , discussing new three-step laser ionization schemes. Rydberg level convergences were studied and the accuracy of the ionization level was improved.

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## Fingerprinting heavy elements via Laser Resonance Chromatography: First demonstrations on Lu<sup>+</sup>

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Atoms of different elements possess distinct spectra which serve as their fingerprints. Beyond providing information about the internal atomic and nuclear structure, knowledge of their spectra has allowed their identification in extragalactic stars and even neutron star mergers. However, very little is known about elements beyond fermium ( $_{100}\text{Fm}$ ), which can only be synthesized in trace amounts in nuclear fusion-evaporation reactions. With scarce production yields below one atom per second, traditional fluorescence methods are insufficient for the spectroscopy of these elements. Given the need for alternatives, a new method called Laser Resonance Chromatography (LRC) was conceived, which doesn't rely on detection of fluorescence. In LRC, after resonant excitation, ions in different electronic states are separated via their distinct mobilities in buffer gas. Here, with an experimental setup we recently commissioned, we present results from the first demonstration done on lutetium ( $_{71}\text{Lu}$ ). We studied a ground-state transition in Lu<sup>+</sup> ions, and the hyperfine structure constants and isotope shifts that we derived for it are in excellent agreement with values known from laser-induced fluorescence. With lutetium being an electronic homologue of the element lawrencium ( $_{103}\text{Lr}$ ) for which not even a single atomic transition has been reported till date, this concretely demonstrates the viability of our method and opens a new avenue for laser spectroscopy of the heaviest elements.

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## Plans for laser spectroscopy at the proton drip line

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At the edges of the nuclear landscape, a rare form of radioactive decay occurs where the nucleus emits a proton. But what is the shape of the nucleus in the moments before it emits a proton? And how does the shape of the nucleus change when the proton becomes unbound? Studying nuclei at the proton drip line with laser spectroscopy may help to provide insights into these questions.

Laser spectroscopy measures the hyperfine structure of atoms, an atomic fingerprint that allows nuclear properties (e.g. spin, electromagnetic moments and charge radii) to be measured. For example, the charge radius tells us about the proton distribution in the nucleus i.e. its shape. By measuring nuclei across the proton-drip line (beyond which proton decay occurs), we hope to gain a unique insight into how a single proton can influence the behaviour of the whole nucleus.

In this talk, I will introduce the concept of proton emission from a nucleus, describe how laser spectroscopy can measure fundamental nuclear properties and outline my plans for measuring the shape of nuclei at the proton drip line. I will outline my plans to measure proton-rich nuclei at ISOLDE, utilising the CRIS experiment and the newly developed PI-LIST setup, as well as future plans to continue studies at the new RISE setup, recently integrated into the BECOLA facility at FRIB.

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## Implantation of pure Fe-55 into microcalorimeters for activity standardization measurements

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Radionuclide metrology techniques, as currently used for activity standardization, show a large variety of measurement uncertainties –from permille accuracy, e.g., for the  $\alpha$ -decaying isotope Am-241 ( $T_{1/2} = 432$  a) up to few percent for Fe-55 ( $T_{1/2} = 2.73$  a), which decays by electron capture. To reduce such uncertainties, a new standardization technique using direct ion beam implantation of the pure radionuclide into metallic microcalorimeters (MMCs) is explored within the European project PrimA-LTD. The intrinsically high energy resolution of such devices additionally allows for determination of electron capture probabilities with unprecedented accuracy, in this way enables the improvement of theoretical models and correspondingly has a broad impact on radionuclide metrology, nuclear power industry, nuclear medicine and radiopharmacy.

The implantation of 5 Bq of Fe-55 into each minuscule absorber, sized  $0.14 \times 0.14$  mm<sup>2</sup>, of such MMC detectors was performed at the RISIKO mass separator at Mainz university using resonance ionization mass separation and specific focalization and automated pointing. The technique was chosen due to its outstanding element selectivity and overall implantation efficiency guaranteeing the required implantation purity. A novel two-step ionization scheme for iron was identified and characterized in stable Fe-56, implying efficient second and third harmonic generation of the Ti:Sa laser radiation used at RISIKO. One of different strong auto-ionizing states was used for implantation of the Fe-55. In Fe-56, the analysis of a long series of Rydberg states allows to verify the ionization potential and extend the existing data on even parity Rydberg states in Fe. The spectroscopic results will be discussed as prerequisite for the implantation process.

The project has received funding from the EMPIR program 20FUN04 PrimA-LTD from the European Union's Horizon 2020 research and innovation program.

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## Measurement of the shift in the electron affinities of tin isotopes at DESIREE

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The electron affinity (EA) is the energy released when an additional electron is bound to a neutral atom, creating a negative ion. Due to a lack of long-range Coulomb attraction, the EA is dominated by electron-electron interactions, making negative ions excellent systems to probe these effects. A particular example is the determination of the specific mass shift, which is of importance when extracting nuclear charge radii from laser-spectroscopy experiments. However, only very few isotope shifts of the EA have been measured to date.

Berzins et al. <sup>1</sup> investigated the isotope shift of the EA of the two stable chlorine isotopes, <sup>35</sup>Cl and <sup>37</sup>Cl both experimentally and theoretically. A discrepancy in their experimental and theoretical results was then solved by Carette and Goodefroid in 2013, increasing the precision of their calculations beyond the uncertainty of the experimental value.

Consequently, a study of the isotope shift of a large mass range of chlorine isotopes was proposed at the radioactive ion beam facility CERN-ISOLDE and performed in 2024 using the GANDALPH spectrometer [3], which was successfully used to determine EAs of radioisotopes previously [3,4]. Here, we will present the results of this measurement campaign and give an outlook on future experiments using the charge exchange process to produce negative ions.

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- [4] D. Leimbach et al. Nat. Comm 11, 3824 (2020)

## Plenary / 185

**Laser Probing of Rare Isotopes: Krypton, Radium, and Beyond****Author:** Peter Mueller<sup>1</sup><sup>1</sup> *Argonne National Laboratory***Corresponding Author:** pmueller@anl.gov

Laser excitation and manipulation techniques offer unique control of an atom's external and internal degrees of freedom. The species of interest can be selectively captured, cooled, and observed with high signal-to-noise ratio down to the single atom level. Moreover, the atom's electronic and magnetic state populations can be precisely manipulated and interrogated. Applied in nuclear physics, these techniques are ideal for precision measurements in the fields of fundamental interactions and symmetries, nuclear structure studies, and isotopic trace analysis.

In this talk, I will concentrate on recent advances in Atom Trap Trace Analysis (ATTA) as a highly selective and sensitive atom counting technique. It has now been established as a routine tool in the geosciences for radiokrypton dating of ancient groundwater and glacial ice samples on timescales of a few ten thousand to a couple million years. The isotope of interest here is the cosmogenic krypton-81 with its half-life of 230,000 years and its isotopic abundance at the parts-per-trillion level in the atmosphere. I will introduce the basic principles and recent progress of the ATTA technique and present selected applications with their impact on understanding groundwater resources and paleoclimatic changes.

I will also present short updates on our experimental effort to measure the permanent electric dipole moment of Radium-225 via laser cooling and trapping, and on a recent milestone in performing collinear laser spectroscopy of rare nuclei at Argonne's ATLAS facility.

This work is in part supported by the U.S. DOE, Office of Science, Office of Nuclear Physics, under contract DE-AC02-06CH11357.

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**Collinear Laser Spectroscopy on Neutron-Deficient Al Isotopes at RISE/ BECOLA****Author:** Brooke Rickey<sup>1</sup>

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At the BEam COoling LAser spectroscopy (BECOLA) facility at the Facility for Rare Isotope Beams (FRIB), a Resonance Ionization Spectroscopy Experiment (RISE) instrument has been newly commissioned. This addition to the BECOLA facility will allow for laser spectroscopy to be conducted through both collinear fluorescence and resonant ionization methods back to back in the same beamline. The details of the commissioning will be discussed, including offline <sup>27</sup>Al measurements of hyperfine coefficients on multiple transitions taken in preparation for an online experiment at FRIB. The debated proton-halo structure in <sup>22,23</sup>Al will be directly addressed by determining the charge radii and electromagnetic moments through the isotope shift and hyperfine structure. A large reaction cross section 1 and a large isospin asymmetry in the mass A = 22 system [2] suggest proton halo structures in <sup>23</sup>Al and <sup>22</sup>Al, respectively. However, the last proton presumably occupies the *d*<sub>5/2</sub> orbital in the ground state, making the proton halo structures' existence not decisive. The first online results obtained with RISE from the experiment scheduled for May 2024 will be discussed.

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## Collinear laser spectroscopy in neutron-rich Ru

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The region of refractory metals below tin exhibits a diverse spectrum of nuclear phenomena, i.e., strong deformations and shape coexistence. Particularly, in the neutron-rich Ru isotopes, there are hints for triaxial ground state deformations. To investigate nuclear ground-state properties of short-lived isotopes with collinear laser spectroscopy, a new collinear setup, ATLANTIS –the Argonne Tandem hall LAser beamline for aTom and Ion Spectroscopy–was installed at the low-energy branch of CARIBU at Argonne National laboratory. There, the CARIBU californium-252 fission source can uniquely produce sufficiently intense low-energy ion beams of neutron-rich isotopes in this part of the nuclear chart.

Laser spectroscopy was successfully performed in  $^{96,98-102,104,106-114}\text{Ru}$  and charge radii as well as electromagnetic moments were extracted. In this talk, the results will be presented and compared with the latest Brussels models BSkG1, BSkG2 and BSkG3 which are energy density functional calculations of the Skyrme type that include triaxiality. Furthermore, an outlook of future laser spectroscopy endeavors at Argonne National Laboratory will be given.

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## On the use of charge distribution in nuclei to constrain effective interactions

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The key ingredient for mean-field calculations in nuclear structure is the effective interaction which models the strong force in the nuclear medium. Such interactions usually depend on a set of parameters fitted to properties nuclei and infinite nuclear matter.

These interactions can suffer several limitations and problems. For example, since they are usually adjusted on properties of observed nuclei close to the valley of stability, their predictive power for exotic and super-heavy nuclei may be questionable. Furthermore, unphysical finite-size instabilities can sometimes appear when these interactions are used to calculate properties of nuclei which have not been considered to constrain their parameters. These unwanted features then make them of very limited interest. These instabilities can appear in various channels and therefore have scalar, vector, isoscalar or isovector characters.

It was shown that the formalism of the linear response in infinite-nuclear matter can be used to avoid such instabilities for the construction of zero-range interaction (of Skyrme type). Although such a formalism was also developed for finite-range interactions (Gogny type), the calculations for the linear response are much more time-consuming and can hardly be incorporated in the procedure used to fit their parameters.

I will discuss how the scalar-isovector instabilities are related to the distributions of protons and neutrons in nuclei and how, in turn, information on charge density distributions can be used to prevent these instabilities. Beside the avoidance of instabilities, information about the charge distribution can lead to a better balance between the different contributions to the binding energy of nuclei and



their evolution with mass and asymmetry. I will show that the use of constraints on charge distributions from a set of chosen nuclei can be used to avoid the appearance of scalar-isovector instabilities and discuss how this could improve the predictive power of the mean-field calculations.

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## Radioactive molecule spectroscopy towards searches for BSM physics

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Molecules that contain heavy and radioactive nuclei can be highly sensitive to a number of nuclear observables of interest, such as the typically studied nuclear magnetic dipole and electric quadrupole moments, but also symmetry-violating hadronic, leptonic, and nuclear moments.

Precision experiments based on heavy and polar radioactive molecules have been proposed as being potentially the most sensitive probes to pin down the level of time-reversal violation in the fundamental forces. Significant technical developments are necessary to bridge the gap between radionuclide production and the techniques that have been developed for high-precision experiments with stable molecules, however. Therefore, global efforts are invested in enabling precision searches for beyond-the-Standard-Model physics with radioactive molecules, along multiple technical directions.

In this talk, the opportunities for fundamental and nuclear physics research with radioactive molecules will be overviewed, followed by a summary of the experimental techniques that have been developed for the type of experiments that radioactive molecules are envisioned for. A summary of recent activities on the production and study of radioactive molecules at CERN-ISOLDE will follow.

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## High accuracy predictions of properties of heavy atoms and molecules and evaluation of uncertainties.

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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 be reliable and useful in experimental context, theoretical predictions should be based on high accuracy calculations. 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 many-electron systems. This approach can be used to obtain ionization potentials, electron affinities, excitation energies, hyperfine structure parameters, and other atomic properties, and a variety of molecular properties. It has been shown to be extremely reliable and to have very strong predictive power. Recently, we have developed a scheme that allows us to use extensive computational investigations to assign uncertainties on the theoretical predictions<sup>1</sup>, facilitating the use of these predictions in experimental context.

A brief introduction to the relativistic coupled cluster method will be provided and the new development for estimation of uncertainties will be presented. The talk will focus on recent successful applications of the coupled cluster approach to atomic and molecular properties, in particular in connection to recent and planned experiments [2-3 and yet unpublished work].

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The electron affinity of astatine  
Nature Comm. 11, 3824 (2020)

[2] A. A. Kyuberis, L. F. Pašteka, E. Eliav, H. A. Perrett, A. Sunaga, S. M. Udrescu, S. G. Wilkins, R. F. Garcia Ruiz, and A. Borschevsky  
Theoretical determination of the ionization potentials of CaF, SrF, and BaF  
Phys. Rev. A 109, 022813 (2024)

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Nuclear charge radii of silicon isotopes  
<https://arxiv.org/abs/2309.02037>

## Plenary / 145

### Radioactive molecular ion beams at CERN-ISOLDE

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The ISOLDE facility at CERN provides radioactive ion beams of nuclides produced in reactions between 1.4-GeV protons and thick targets using the Isotope Separation On-Line (ISOL) technique. The formation of volatile molecules has been used as a method to deliver beams of otherwise non-volatile release-limited elements [1-5]. Molecular sideband extraction is also used to improve beam purity. The availability of molecular beams additionally provides opportunities for fundamental physics studies [6-11].

We present our work on molecular ion beam production at CERN-ISOLDE using actinide targets and Forced Electron Beam Induced Arc Discharge (FEBIAD)-type ion sources [12]. Beam composition

studies are presented using: the ISOLTRAP Multi-Reflection Time-of-Flight Mass Spectrometer (MR-ToF MS) [13], online  $\gamma$ -ray spectroscopy at the ISOLDE tape station [14,15], and off-line  $\alpha$ - and  $\gamma$ -ray spectrometry of ion-implanted samples.

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### Plenary / 96

## Ultra-trace analysis of radionuclides with laser ionization mass spectrometry

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**Co-authors:** Clemens Walther<sup>1</sup>; Darcy van Eerten<sup>1</sup>; David Ohm<sup>1</sup>; Laura Leifermann<sup>1</sup>; Tobias Weissenborn<sup>1</sup>

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Resonant laser secondary neutral mass spectrometry (rL-SNMS) combines the spatial resolution traditional ToF-SIMS with the elemental selectivity of resonant laser ionisation. This quasi non-destructive method is an ideal choice for the analyses of micron sized fragments of nuclear fuel, so called “hot particles” from the Chernobyl exclusion zone 1. With this method actinides in single radioactive can be detected, down to E7 atoms of a single isotope [2]. The relative <sup>238</sup>Pu content of the particles can be determined by suppressing the dominant <sup>238</sup>U in spent fuel. The isotopic fingerprint of these particles allows to links them to the nuclear accident as well as identifying particles with unusual isotope ratios. The current capabilities of the RIMS-system are presented in this talk, with an outlook on further developments of the method and application to ultra-trace analysis.

1 DOI:10.1039/9781837670758-00001

[2] DOI:10.1126/sciadv.abj1175

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## The current status of S3LEB at GANIL

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S3LEB (Super Separator Spectrometer-Low Energy Branch) is a low energy radioactive ion beam facility, which will be employed for the study of exotic nuclei, under commissioning as a part of GANIL-SPIRAL2 facility 1. High intensity primary beams, delivered by the superconducting LINAC of the SPIRAL2 facility, will allow for increased production rate for nuclear fusion evaporation reaction, thus will facilitate exploration of some critical areas of the nuclide chart with low production cross section and shorter lifetime. The produced ions will be separated by the recoil separator S3 and will be sent to the S3LEB facility at the focal plane of S3 [2].

S3LEB is a gas cell setup followed by radiofrequency quadrupole units, which allows selective ionization of radioactive ions of interest as well as efficient transmission of the ions to an MR-TOF (Multi-Reflection Time of Flight separator) for further beam purification and detection. The ions thermalized and neutralized inside the buffer gas cell are selectively laser ionized either inside the gas cell or in a hypersonic gas jet environment created after the gas cell using a De-Laval nozzle. The S3LEB set up has been commissioned off-line [3,4] and is now being installed at the focal plane of S3, in preparation for on-line commissioning.

Here we present the status of the set up as well as the recent off-line measurements, including in-gas-cell and in-gas jet laser spectroscopy of erbium isotopes in combination with trapping, selection and mass measurement with the multi-reflection time-of-flight mass spectrometer PILGRIM.

Finally, the road map to online commissioning will be presented.

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## Mass measurements of exotic nuclides in the vicinity of $^{100}\text{Sn}$ and their implications to nuclear structure

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The heavy  $N = Z$  nuclei and the nuclei in their vicinity are highly interesting to study; they can provide important insights about nuclear structure, symmetries and interactions and have a high impact in modelling nuclear astrophysics processes ( $rp$ -process,  $\nu p$ -process). A few examples of the striking phenomena are the formation of high-spin isomeric states, the direct and/or  $\beta$ -delayed proton emission from ground or excited states and the strong resonances in Gamow-Teller transitions close to the proton dripline. The FRS Ion Catcher (FRS-IC) experiment at the in-flight fragment separator FRS at GSI enables highly accurate direct mass measurements ( $\delta m/m \sim 10^{-8}$ ) with thermalized projectile and fission fragments by combining a cryogenic stopping cell and a multiple-reflection time-of-flight mass spectrometer. Supported by mass measurements at the FRS-IC within FAIR Phase-0, including the first direct mass measurement of  $^{98}\text{Cd}$ , the evolution of Gamow-Teller transition strengths (B(GT)) for even-even  $N = 50$  and  $N = 52$  isotones was studied [1]. Comparing experimental and theoretical B(GT) values sheds more light on the controversy around the mass of  $^{100}\text{Sn}$  [2,3,4]. Additionally, the excitation energy of the long-lived isomer in  $^{94}\text{Rh}$  was determined for the first time; comparing the value of which with shell model calculations allows to understand the level ordering and spin-parity assignments of the observed states [1]. The mass of  $^{93}\text{Pd}$  was measured directly for the first time, reducing the mass uncertainty by an order of magnitude. This helps to further unravel the riddle surrounding the exotic decay modes of the  $(21^+)$  high-spin isomer of  $^{94}\text{Ag}$ , the investigations of which were summarized in Ref.[5,6].

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### MR-ToF mass measurements of the isomeric states in $^{94}\text{Ag}$ produced with a hot cavity at IGISOL

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The  $N=Z$  nucleus  $^{94}\text{Ag}$  has intrigued physicists for decades thanks to its unique decay modes, long-living isomeric states, and structure. Most notably, the existence of an elusive two-proton decay channel in its spin  $21^+$  isomeric state has been a subject of debate since its first reports in 2006 [1]. Subsequent investigations of  $^{94}\text{Ag}$  have not found evidence of two-proton emission, although other decay channels, such as the one-proton emission, have been reported [2]. This has raised interest to study further the feasibility of the two-proton emission of  $^{94}\text{Ag}$ .

Comparing spectroscopic data with atomic mass measurements points to a discrepancy of 1.4 MeV in the  $21^+$  state energy, suggesting that the two-proton decay is energetically forbidden [3]. A direct mass measurement of the  $21^+$  state is required to impose constraints to the possible two-proton emission channels.

The masses of the isomeric states of  $^{94}\text{Ag}$  have been measured for the first time, employing a combination of a hot cavity catcher laser ion source [4] and a Multi-Reflection Time-of-Flight Mass-

Separator (MR-ToF-MS) at the Ion Guide Isotope Separator On-Line (IGISOL) - facility. In this contribution I will present an overview of the experiment and the masses of the  $^{94}\text{Ag}$  states.

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## Optical spectroscopy of the silver isotopic chain

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How does the size and deformation of the silver nucleus evolve as a function of neutron number as one moves between two exotic neutron shell closures,  $N=50$  and  $N=82$ , and can modern nuclear theoretical methods accurately predict the trends? To address this question, experiments in recent years have been performed at the IGISOL facility using collinear laser spectroscopy [1] and in-source spectroscopy [2], while at the ISOLDE facility, CERN, the CRIS experiment was used to provide complementary information and to extend the study to additional isotopes on either side of the valley of stability.

In addition to the charge radius, magnetic dipole moments provide sensitive information on the purity of the nuclear wavefunction, serving as an additional stringent test for theoretical calculations. In a wider perspective, with atomic number  $Z = 47$ , the silver isotopes are located between the magic ( $Z = 50$ ) tin isotopes and the strongly-deformed region around and below  $Z = 45$ .

This contribution will provide a comprehensive picture of the evolution of deformation in this region of the nuclear chart by presenting the evolution of the nuclear charge radius and the nuclear electromagnetic dipole and quadrupole moments of exotic silver isotopes. A summary of the measurements using the different techniques will be highlighted.

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[2] M. Reponen et al., *Nature Comm.* 12 (2021) 4596.

### Plenary / 133

## In search of increasingly exotic nuclides at TITAN

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As nuclides become increasingly exotic, production yields fall off; contamination increases; and, often the half lives drop. To meet these challenges, developments at the TITAN-TRIUMF facility are continually underway. Its Multi-Reflection Time-Of-Flight (MR-TOF) mass separator has become the preferred tool in probing the limits of radioactive-ion-beam production at TRIUMF via high-precision mass determinations. These measurements are essential for studying evolving nuclear structure as well as for investigating the r- and rp-process in nucleosynthesis. I will present recent results from the MR-TOF and TITAN at large.

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## Recent mass measurements at ISOLTRAP

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High-precision mass measurements of radioactive ions are used to determine nuclear binding energies, which reflect all forces acting in the nucleus and are used to study among others nuclear structure, nuclear astrophysics, and weak interaction.

For this, the ISOLTRAP mass spectrometer at ISOLDE/CERN 1 uses various ion traps, including a tandem Penning-trap system and a multi-reflection time-of-flight mass spectrometer (MR-ToF MS), where the latter is suitable of both mass separation and fast, precise mass measurements.

In this contribution, the first direct mass measurements of neutron-deficient <sup>97</sup>Cd and the excitation energy of the <sup>97m</sup>Cd high-lying isomer along with a precise measurement of <sup>98</sup>Cd in the immediate vicinity of self-conjugate doubly magic <sup>100</sup>Sn ( $N = Z = 50$ ) will be presented together with measurements of neutron-rich <sup>209,210</sup>Hg.

Additionally, the current setup of the ISOLTRAP experiment is introduced together with the future re-bunching system using a new Mini-RFQ behind the MR-ToF MS to enable measurements of extremely isobaric contaminated beams.

1 D. Lunney et al., J. Phys. G: Nucl. Part. Phys. 44 (2017) 064008

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## High-precision Penning-trap mass measurements of heavy and superheavy elements with SHIPTRAP

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Speculation about the existence of elements heavier than uranium started in the late 19<sup>th</sup> century. Thanks to an increased understanding of nuclear structure and decades of developments, transuranic and eventually superheavy elements were discovered [2]. The latter owe their existence to nuclear shell effects, which enhance their stability [3]. The strength of these effects can be quantified through direct mass measurements performed with Penning traps [4], providing invaluable information on the nuclear shell evolution. Furthermore, the excitation energies of low-lying, long-lived metastable nuclear states, common in the heavy nuclei, can be obtained from the directly measured masses, complementing decay spectroscopy studies and providing further information.

The goal of the SHIPTRAP experiment is to study heavy and superheavy nuclei produced via fusion-evaporation reactions at rates well below one particle per hour. Nuclei produced at such low rates are accessible thanks to the implementation of a cryogenic buffer-gas stopping cell [5] and the development of the Phase-Imaging Ion-Cyclotron-Resonance technique [6]. These enabled the study of more exotic nuclei [7]. In this contribution, the latest results, obtained as part of the FAIR phase-0 campaign at GSI, will be presented. These comprise measurements on the ground-state masses and isomeric-state-energy measurements of nuclides from <sup>196</sup>Bi to <sup>257</sup>Rf.

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## Penning-trap eigenfrequency measurement using single laser-cooled ions

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A new method for the determination of the eigenfrequencies of laser-cooled ions in a Penning trap has been recently demonstrated. It relies on the measurement of the ion's motional amplitude using the scattered photons when an internal optical electric dipole transition is addressed by lasers [1]. Compared to other techniques, it is universal regarding the mass-to-charge ratio, it is non-destructive, and allows the observation of motional amplitudes of only a few micrometers, which drastically reduces the systematic uncertainties.

In this contribution, we will present the measurement of the cyclotron-frequency ratios of several calcium isotopes ( $^{42,44,48}\text{Ca}^+$  vs  $^{40}\text{Ca}^+$ ) using this optical detection method [2]. Single ions are laser-cooled to temperatures in the order of millikelvin [3] and subsequently probed by an oscillating electric field close to one of its eigenfrequencies. The motional amplitude is readout using photon-counting and photon-imaging units while re-cooling the system to the Doppler limit after excitation.

The optical method has also been proved with two-ion Coulomb crystals, yielding the first measurements of the six eigenfrequencies of a balanced ( $^{40}\text{Ca}^+ - ^{40}\text{Ca}^+$ ) and unbalanced ( $^{42}\text{Ca}^+ - ^{40}\text{Ca}^+$ ) crystal, previously studied theoretically in Ref. [4]. The uncertainty from these measurements and the prospects for improvement by accessing the quantum regime will be briefly discussed [5]. We will also present the status of the recent upgrade of our Penning-trap experiment after the installation of a new cryogen-free superconducting magnet.

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## LEMING: Towards measuring the gravitational acceleration $g$ of Muonium

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Muonium ( $\text{Mu} = \mu^+ + e^-$ ) is a purely leptonic, two-body exotic atom amenable for precision measurements of fundamental constants ( $m_\mu, \mu_\mu$ ) and tests of bound state QED. Mu also offers the possibility to directly test the coupling of gravity to second generation elementary (anti)leptons, a system

where there are no contributions to the mass by the strong interaction. Hence, such measurements are complementary to the new results of the ALPHA collaboration 1.

The newly approved LEMING (LEptons in Muonium INteracting with Gravity) experiment located at the Paul Scherrer Institut (PSI) aims to improve laser spectroscopy measurements on Mu and to measure Mu in free fall. However, state-of-the-art, vacuum Mu sources rely on thermal emission, limiting the feasibility of both scientific goals.

A novel way of Mu production was demonstrated using a thin layer of superfluid helium. We have achieved the production of a Mu beam with ~10 % conversion efficiency and ~30 mrad angular divergence. These results allow for measurements of g on Mu with a precision of ~1% using atom interferometry and to improve the fractional precision of Mu 1S-2S measurements by more than an order of magnitude, compared to thermal sources.

In this talk the first observation of a vacuum Mu being emitted from superfluid helium and an initial characterisation of the novel Mu source will be presented. Furthermore, the resulting prospect to do spectroscopy and measure g will be discussed.

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# Absolute charge radii measurements of potassium and chlorine

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Muonic atom spectroscopy is a technique that studies the atomic transitions between levels that are occupied by muons orbiting a nucleus. Due to the heavier mass of muons with respect to that of

electrons, its atomic orbitals will be substantially closer to the nucleus. Consequently, the sensitivity to nuclear effects is enhanced. In particular, muonic atoms have an increased sensitivity to the finite size correction ( $\sim 10^7$  compared to electronic atoms). As a result, absolute nuclear charge radii can be extracted, providing invaluable input for laser spectroscopy experiments in the form of benchmarks 1.

By employing a high-pressure hydrogen cell, with a small deuterium admixture, it became possible to reduce the required target quantity from 10 mg to about 5  $\mu\text{g}$ . This opens the door to measurements on long-lived radioactive isotopes and materials not available in large quantities [2]. In 2022, we performed an experiment that showed implanted targets could be used for the spectroscopy [3]. As a result, samples that have been prepared by employing mass separation and subsequent implantation, can be measured with our technique. Following this success, we did another experimental campaign in October 2023 with the goal of measuring the absolute charge radius of potassium and chlorine isotopes.

In this contribution, we shall report on the experimental method and recent results obtained for muonic x-ray measurements on  $^{39,40,41}\text{K}$  and  $^{35,37}\text{Cl}$ , as well as their implication for future research.

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## Ultra-cold Cs trap for magnetic octupole moment studies and coherent gamma generation

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The atom-trap facility at the Ion-Guide Isotope Separator On-Line (IGISOL) at the University of Jyväskylä has been developed for cooling and trapping a chain of isotopes and isomers of caesium 1. This would allow a high-precision spectroscopy from which a nuclear magnetic octupole moment can be deduced, an important parameter which helps validate nuclear theory and reveal insight on the nuclear structure [2]. Moreover, a Bose-Einstein condensate of  $^{135\text{m}}\text{Cs}$  isomers was shown to be a potential candidate for a long-sought coherent gamma-ray source, an intriguing result of the coherent nature of the degenerate ensemble [3]. The Cs isotopes and isomers are produced via proton-induced fission of a natural uranium target in a helium buffer gas filled ion guide, extracted via gas flow, accelerated electrostatically to 30 keV, mass-separated, and finally delivered to a cold-atom chamber. Installed inside the chamber is a thin yttrium foil where implanted Cs ions can be neutralised and released using resistive heating. A special coating applied on the inner surface of the chamber then allows thermalisation of hot Cs atoms, thereby facilitating a magneto-optical trap (MOT), the initial stage of a cooling and trapping scheme. Well-established optical cooling methods such as optical molasses and degenerate Raman sideband cooling (DRSC) are subsequently applied to obtain a temperature suitable for a probing activity of interest, and ultimately reach the quantum degenerate regime of BEC.

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## Towards the study of the Bohr-Weisskopf effect in short lived nuclei using laser-rf double-resonance spectroscopy.

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Using convectional collinear laser spectroscopy techniques, the Bohr-Weisskopf effect (BWE) is frequently found to be at a similar level to the experimental uncertainty. Therefore, the study of this effect has been mainly limited to stable isotopes, where higher precision can be obtained. Despite the limited information, this effect could in principle provide significant new information on both the composition of nuclear magnetism and its spatial distribution. At the VITO beamline at ISOLDE, a new programme of research into the BWE has been initiated. Here, a new beamline end station is under construction, in which laser-rf double resonance will be performed. Using this technique, the resolution required for the widescale study of this observable will become available. In this contribution, the developments undertaken will be reviewed and recent results on the BWE presented.

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## Probing the nuclear magnetic octupole moment of trapped Sr ions

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At the Institute for Nuclear and Radiation Physics of KU Leuven (IKS) we started a project to measure data on the magnetic octupole moment ( $\Omega$ ) of single valence radioactive nuclei. While currently this observable has only scarcely been measured, and is thus poorly understood, preliminary shell model and Density functional theory (DFT) calculations indicate  $\Omega$  may display a strong sensitivity to nuclear shell effects, even stronger than the dipole moment. It may also be well suited to probe the distribution of neutrons within the nucleus, and study fundamental properties of nucleons of stable and radioactive isotopes. This objective presents several challenges, both technical and scientific, as there are presently no methods that reach the precision required to measure  $\Omega$  for short-lived isotopes of any element. In this context, the first study will be performed on the stable  $^{87}\text{Sr}^+$ . With 49 neutrons,  $^{87}\text{Sr}^+$  is characterized by a single hole in the N=50 closed shell, which makes it more easily compared with a variety of theoretical calculations. Once measurements with  $^{87}\text{Sr}$  are demonstrated, it could be possible to extend them to the long-lived  $^{83,85,89}\text{Sr}^+$  here at IKS. A non-zero  $\Omega$  leads to small energy shift of the hyperfine structure. We aim to measure these splitting with a precision of the order of 1-10 Hz on the hyperfine intervals, which should result in a measurement of  $\Omega$  with a precision of 10%. This has been demonstrated feasible with stable  $^{137}\text{Ba}^+$ , homologue of  $\text{Sr}^+$ , inside ion traps 1. This contribution aims to offer a broad understanding of the project and present the latest developments in the laboratory.

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## CERN-ISOLDE's new high-resolution laser ion source PI-LIST: Results, characteristics, and developments

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On-line in-source laser resonance ionization is a highly sensitive tool for nuclear structure investigations [1]. While the efficiency of this technique is unrivaled, the experimental resolution is ultimately limited by Doppler broadening in the hot cavity required to ensure atom volatilization. At typical operation temperatures around 2000 °C, this leads to a several GHz limit, whereas precise measurements of nuclear magnetic and quadrupole moments often require resolving hyperfine structure splittings well below the GHz regime.

A new laser ion source design has been implemented at CERN-ISOLDE to provide in-source spectroscopy capabilities down to experimental linewidths around 100 MHz, an order of magnitude below usual limitations. It is based on the Laser Ion Source and Trap (LIST) [2], tailored for high purity ion beam production. In the new so-called Perpendicularly Illuminated LIST (PI-LIST) mode [3], a crossed laser / atom beam geometry reduces the effective Doppler broadening by addressing only the transversal velocity components of the effusing atom ensemble –a method that had previously become the standard for very successful off-line experiments at Mainz University [4, 5, 6].

We report on the first-time on-line application of the PI-LIST [7] for investigations on octupole deformation in neutron-rich actinium isotopes [8]. Limitations, prospects and developments are discussed, and several application cases mainly focused on the lanthanide and actinide region are presented.

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## In-source Laser Spectroscopy Studies of Neutron-rich Thallium at IDS/ RILIS-ISOLDE

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Laser spectroscopy is one of the most powerful tools for studying ground and isomeric state nuclear properties. By observing small changes in atomic transitions, we can deduce the nuclear spin, electromagnetic moments, and changes in mean-square charge radii across long chains of isotopes. This allows us to study how the shapes and the configurations of the nuclei vary along the chain and hence to test our models that attempt to describe how nuclear structures evolve across the chart.

In this contribution, I will present the results from hyperfine structure and isotope shift studies of neutron-rich  $^{207-209}\text{Tl}$  performed at the ISOLDE Decay Station (IDS), combined with the application of the Laser Ion Source and Trap (LIST) to suppress the isobaric contamination typical to this mass region. The changes in the mean-square charge radii and magnetic dipole moments were extracted. The results display a kink in the mean-square charge radii along the Tl isotopic chain when crossing the N=126 shell closure. The magnetic dipole moments for  $1/2^+$  thallium ground states have a large jump at N=126. Theoretical calculations including particle-vibrational coupling with the self-consistent theory of finite Fermi systems based on energy density functional are used to model the data [2].

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## On-line resonance ionization laser ion source development at the RAON ISOL facility

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Resonance ionization laser ion source (RILIS) has been developed as part of the ISOL ion sources at RAON in the Institute for Rare Isotope Science, Korea. The RAON RILIS based on Ti:sapphire lasers has been developed with a long laser beam transport system over 30 m. To develop optimal laser ionization schemes and investigate the RILIS efficiency, an off-line test facility adjacent to the RILIS laser room has been newly equipped. After the successful operation of RILIS with stable Sn and Al isotopes at the off-line test facility, the current effort aims at the on-line operation of the RAON RILIS to provide radioactive ion beams to the applications, such as collinear laser spectroscopy (CLaSsy) and mass measurement system (MMS).

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## Double-beta decay Q-value measurements with the JYFLTRAP Penning trap

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The observation of double-beta decays and double-electron captures have become an important tool in the search for physics beyond the Standard Model (SM). These decays have been proposed to decay by emitting either two neutrinos or no neutrinos. While the two neutrino mode has been observed, the proposed neutrinoless decay mode requires the neutrino to be its own antiparticle (a Majorana

particle), which would be a violation of the SM. To determine the suitability of an isotope for these observations, the energy released in the decay (Q-value) needs to be known precisely in order to calculate its half-life (generally  $\geq 10^{25}$  a), and thus the feasibility of observing the neutrinoless decay mode and to separate the decay signal from background.

In three recent measurements at the Ion Guide Isotope Separator On-Line (IGISOL) facility [2] in the University of Jyväskylä, the JYFLTRAP double Penning trap [3] employing the Phase-Imaging Ion-Cyclotron Resonance (PI-ICR) method [4] was used to determine the  $Q_{\beta-\beta^-}$  of  $^{104}\text{Ru}$ ,  $^{122}\text{Sn}$ ,  $^{142}\text{Ce}$  and  $^{148}\text{Nd}$ , and  $Q_{ECC}$  of  $^{120}\text{Te}$ . In addition, the precisely known  $Q_{ECC}$  of  $^{102}\text{Pd}$  and  $^{150}\text{Nd}$ , and  $Q_{\beta-\beta^-}$  of  $^{124}\text{Sn}$  were re-measured. The ions were produced using two electric discharge ion sources. A precision of  $\sim 100$  eVs was reached for the Q-values. Most of our measurements are in agreement with their literature values in the Atomic Mass Evaluation [5]. In my contribution, I will present the JYFLTRAP measurement setup, the PI-ICR measurement technique and initial results of our measurements.

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## High precision decay energy measurements of low Q-value beta decays with JYFLTRAP at IGISOL

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High-precision measurements of single  $\beta^\pm$  decays or electron capture (EC) are the most model-independent methods to determine the absolute scale of the (anti)neutrino mass. Decay transitions with the lowest possible Q value are desirable. Currently, only three nuclei with low ground-state-to-ground-state (gs-to-gs) decay Q values are employed for direct neutrino-mass measurements [1-3]. Further explorations for low Q-value ground-state-to-excited-state (gs-to-es)  $\beta$  decay or EC transitions are crucial. In addition to the slightly positive Q values, the slightly negative Q values can also be of interest in seeking for a new type of transition process, like the virtual radiative “detour” transitions (RDT) 1. A precise and accurate determination of the decay Q value is extremely important in the context of searches for the absolute (anti)neutrino mass scale or for RDT study, with potential implications for low-energy solar-neutrino detection.

Recently, multiple gs-to-gs low-Q-value beta-decay candidates ( $^{72,76,77}\text{As}$ ,  $^{75}\text{Se}$ ,  $^{75}\text{Ge}$ ,  $^{95-97}\text{Tc}$ ,  $^{111}\text{In}$ ,  $^{131}\text{I}$ ,  $^{136}\text{Cs}$ ,  $^{155}\text{Tb}$ , and  $^{159}\text{Dy}$ ) have been measured with JYFLTRAP at the University of Jyväskylä [1-3]. The measured high-precision Q values, coupled with nuclear energy level data, are used to determine the energetic permissibility of these low Q-value gs-to-es beta decay candidates, and ascertain the absolute Q value. Subsequently, the suitability of these beta decays with low Q values for direct searches for neutrino mass or for RDT study can be inferred. In this report, the state-of-the-art Penning Trap experimental techniques to determine the gs-to-gs Q value to a relative uncertainty of  $\sim 10^{-9}$ , along with the Q-value measurement results of select cases for neutrino mass determination, RDT study, potential implications for low-energy solar-neutrino detection. will be discussed.

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## Plenary / 115

## Update on TRIUMF's resonant ionization laser ion source(s) and the nuclear spin polarized beams program

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The laser applications group at TRIUMF - Canada's particle accelerator centre is tasked to provide clean and intense beams of radioactive isotopes for user experiments. This is done through in-source laser resonance ionization (running a laser ion source or derivatives thereof). Beam delivery activities and highlights of the RIB delivery and development program of the past years will be described and discussed.

In addition the group is tasked with providing nuclear spin polarized beams for experiments such as beta detected nuclear magnetic resonance spectroscopy - which is used for materials and bio sciences, as well as nuclear structure investigations. With increased demand for specific spin polarized species the combined polarizer- and collinear fast beam laser spectroscopy beamline is undergoing upgrades to facilitate new user programs in collinear fast beam laser spectroscopy, as well as the coupling of the GRIFFIN nuclear decay spectrometer to the polarizer.

Current activities, upgrades and future plans for polarized beams and collinear fast beam laser spectroscopy will be presented.

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## Neither last nor least, just LIST –derivatives of a versatile laser ion source and their applications

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Selective and efficient ionization using multi-step resonant laser excitation processes has become the most versatile and widely used technique in the production and study of exotic species, both for research on their atomic or nuclear structure at the different on-line facilities worldwide as well as for applications in isotope purification for fundamental investigations or for the production of nuclear medical radioisotopes. The key shortcoming of the inevitable occurrence of interfering non-selective surface ionization on hot surfaces of the laser ion source unit has been successfully addressed by the



development and implementation of the laser ion source trap (LIST), which ensures the suppression of the isobaric background by orders of magnitude with only a moderate loss of efficiency [1,2].

Based on the early, rather sophisticated concepts of the LIST formulated 20 years ago [3], several adaptations - both simplifications and specific refinements - have led to a variety of applications. Today, aside from isobar suppression, these focus on direct high-resolution in-source laser spectroscopy on hyperfine structures and isotope shifts of rare species off- and on-line in the (PI)-LIST [4,5]. Furthermore, the recent upgrade to the field ionization (FI)-LIST has paved the way for the precision determination of ionization potentials on exotic species [6]. After a brief review of the development steps from the first LIST concept, the presentation will focus on the investigations carried out on stable and long-lived radioisotopes performed at the off-line RIB facility RISIKO of Mainz University using the PI- and FI-LIST.

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## Poster Sessions / 170

### Optimization and development of RFQ Cooler Bunchers for S3-LEB at GANIL and JetRIS at GSI

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Resonance Ionization Spectroscopy (RIS) probes the atomic structure via multiple step laser ionization of neutralised atoms. Performed in a hypersonic gas jet, the precision of this technique is improved due to reduced Doppler and pressure broadening [1].

At the focal plane of the S3 separator in GANIL, S3-Low Energy Branch (S3-LEB) will perform in-gas-jet RIS to access fundamental properties of exotic nuclei [2], while extracting the ions from the stopping volume via gas flow. This highly selective technique will produce pure beams for further measurements, among which mass measurements by a Multi-Reflection Time-Of-Flight Mass Spectrometer (MR-ToF-MS).

Behind the SHIP velocity filter at GSI, JetRIS uses ion guiding and filament neutralization to inject the fusion products into the gas jet [3]. The photoions are studied using an alpha detector for efficient detection with low background. Future improvements foresee an MR-ToF-MS, which allows for mass-selected ion detection, giving access to long-lived as well as beta-decaying nuclides. Both setups will make use of an MR-ToF-MS, which requires bunched ions. For this, a Radio Frequency Quadrupole Cooler Buncher (RFQcb) is currently commissioned within the S3-LEB setup. Here, ion-trajectory simulations are employed to minimize losses, then results are compared with experimental measurements. The design of the RFQcb of JetRIS is finalised and the commissioning of this buncher coupled to the MR-ToF-MS is foreseen to happen in 2024. Simulations for this bunching unit will accelerate its optimization during the commissioning phase.

In this contribution, the ongoing work to improve the efficiency of the RFQcb for S3-LEB will be discussed, along with the design for the new RFQcb and the last offline characterisation results on JetRIS.

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## Poster Sessions / 79

### Developments towards a high-throughput laser ion source for MEDICIS

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Resonant laser ionization is an efficient and highly selective method for producing radioisotopes. In the laser ion source of ISOLDE –RILIS (Resonance Ionization Laser Ion Source), the laser interaction region is (standardly) inside a metal tube which is heated to temperatures of >2000 degrees Celsius. This heating induces surface ionization from the walls of this so-called “hot cavity”, whilst electron emission from the walls ensures the confinement of laser ions created in the center of the source. If the overall ion load of laser and surface ionized species reaches a certain threshold, the efficient extraction of these ions is compromised. This effect is especially prevalent in facilities like MEDICIS which demand a high ion throughput and fast extraction.

This work aims to present the limits of the current laser ion source at MEDICIS and introduce recent developments towards a new high throughput ion source. The parameters used to describe the plasma inside the ion source are presented. For some of these parameters - like temperature distribution, electron density and neutrals density -, experimental results for comparison with existing models through ion simulations will be shown. Additionally, approaches for stabilizing/improving the ion confinement, which effectively increases the sustainable ion load without hampering the subsequent extraction of the laser ions, will be shown.

## Poster Sessions / 85

### Development and commissioning of HIBISCUS: A new ion beam Radio Frequency Quadrupole Cooler Buncher for high-precision experiments with exotic radioactive ions at NUSTAR/FAIR

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NUSTAR (Nuclear Structure, Astrophysics and Reactions) experiment at FAIR will explore exotic nuclei far from stability. The mass measurements and laser spectroscopy will be performed with the MATS and LaSpec experiments. In order to fully utilise the unique production capabilities at FAIR, the radioactive beams have to be slowed down and bunched for the experiments. For this purpose, a new ion beam cooler-buncher has been built in the JYFL accelerator laboratory of the University of Jyväskylä, Finland, where the device is being commissioned and characterized before transportation to its final location in the low-energy branch of FAIR 1. The cooler-buncher – a Finnish in-kind contribution named HIBISCUS – is a central device as it will transform the beam of ions from the upstream cryogenic stopping cell behind the Super FRS [2] to be suitable for downstream experiments at MATS and LaSpec experimental halls [3]. The device features an enclosed quadrupolar electrode configuration for application of a radio frequency electric field for ion confinement and is filled with helium gas for ion cooling. The axial field is realized with progressively shorter wedge-shaped electrodes placed in-between the radiofrequency electrodes. Ions can be extracted as a continuous beam or collected into a pair of potential wells in subsequent enclosures on the exit side of HIBISCUS, for beam bunching. In this mode, HIBISCUS can be set to deliver bunches either with low energy spread or low temporal spread. Upon extraction, the ions are accelerated back to 6keV of energy to be then sent to downstream setups and experiments.

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## Poster Sessions / 88

### Progress in the development of a collinear resonance ionization laser spectroscopy setup

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The fundamental properties of unstable nuclei are highly related to the nuclear structure and effective nucleon-nucleon interaction, which can be used to study various exotic structures of the unstable nuclei. Laser spectroscopy technique is one of the powerful tools to study the nuclear properties (i.e. spins, moments and radii) by probing the hyperfine structure (HFS) and isotope shift of the corresponding atoms or ions.

To study the unstable nuclei at the radioactive ion beam facilities in China, our research group has developed a collinear resonance ionization laser spectroscopy setup [2]. The setup has been firstly commissioned offline with stable Zn and Ti nuclei by measuring their optical spectra. To further improve the quality of the ion beam and the measurement sensitivity of the setup, a compact Radio-frequency Quadrupole cooler and buncher (RFQ) [3] was implemented, allowing to provide a better beam profile and time structure of the ion bunches.

In this talk, the details of the collinear resonance ionization laser spectroscopy setup as well as the RFQ system will be presented, together with the results from the offline commission experiment. A

planned online laser spectroscopy experiment using this setup at the Beijing Radioactive Ion-beam Facility [4] will also be discussed.

[1] X. F. Yang, S. J. Wang, Wilkins S G, et al. Prog. Part. Nucl. Phys, 129, 104005 (2023).

[2] P. Zhang, H. R. Hu, X. F. Yang, et al. Nucl. Instrum. Methods Phys. Res. B. 541, 37-41 (2023).

[3] Carina Kanitz. Master's thesis, Universitätsklinikum Erlangen (2021)

[4] T. J. Zhang, B. Q. Cui, Y. L. Lv, et al. Nucl. Instrum. Methods Phys. Res. B. 463, 123-127 (2020).

## Poster Sessions / 89

### High precision experimental nuclear physics with the upgraded TITAN Penning trap

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Nuclear physics experiments probe nuclear structure, nucleosynthesis, and fundamental interactions, for which high precision and accurate mass measurements are critical inputs. TRIUMF's Ion Trap for Atomic and Nuclear science (TITAN) facility employs the Measurement Penning Trap (MPET) to measure masses of exotic nuclei to high precision and accuracy with a goal of  $\sim 10^{-10}$ . To improve the resolving power and to reduce the statistical uncertainty in the mass measurement, a higher charge state of the ions can be used. This and other benefits of charge breeding radionuclides like improved beam purification can be realized only at TITAN as it alone combines radioactive ions, charge breeding, and a Penning trap. To fully leverage these advantages, MPET underwent an upgrade to a new cryogenic vacuum system compatible with ions in charge states over  $20+$ . The status of cryogenic Penning trap will be presented, along with the preliminary results from the first radioactive ion beam experiment done with the upgraded trap.

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### Intracavity generation of tripled Ti:Sa laser pulses

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To efficiently laser-ionize many different elements, the spectral range of the Ti:Sa lasers at ISOLDE RILIS is extended with nonlinear processes of second-, third- and fourth harmonic generation (SHG, THG and FHG).

We present a technique to intracavity generate ns pulses in the tripled Ti:Sa range ( $\sim 230\text{nm} - 310\text{nm}$ ) with a Gaussian beam shape and a size comparable to that of the fundamental Ti:Sa output. By generating the 3rd harmonic inside the cavity of the Ti:Sa, the need for tedious beam shaping, which is required in single-pass THG outside the laser cavity, is eliminated.

The setup is less complex than the usual single-pass THG and requires no additional space, since it is located inside the Ti:Sa cavity. Similar performance to that of external frequency conversion has been achieved and a direct comparison of the techniques will be presented.

## Poster Sessions / 94

### The Artemis experiment: Towards high-precision g-factor measurements on highly charged ions

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The ARTEMIS experiment [Quint W et al. 2008 Phys. Rev. A 78 032517] located at the HITRAP facility at GSI in Darmstadt, Germany, aims to measure the magnetic moments of bound electrons in heavy, highly charged ions (HCI) at the  $10^{-9}$  level of accuracy by performing laser-microwave double-resonance spectroscopy. The goal is testing QED in extreme fields including the study of higher-order Zeeman effects [Lindenfels D et al. 2013 Phys. Rev. A 87 023412]. The heart of ARTEMIS is a Penning trap stack inside a superconducting magnet. It consists of two connected Penning traps: a creation trap and a spectroscopy trap. The former is a mechanically compensated trap with open endcaps and equipped with a field emission point for in-trap creation of HCI. The latter is of a dedicated half-open design [Lindenfels D et al. 2014 Hyp. Int. 227 197-207] and electrically compensated. First commissioning has demonstrated successful in-trap ion production, storage, selection and cooling [Kanika et al. 2023 J. Phys. B 56 175001]. To test and develop the experimental setup and methods, a test ion is required which has a fine-structure splitting in the laser-accessible domain as well as a suitable ionisation potential for the in-trap creation. Therefore,  $^{40}\text{Ar}^{13+}$  was chosen while  $^{209}\text{Bi}^{82+}$  will be taken for future measurements. For access to these heavy few-electron ions, ARTEMIS is connected to the HITRAP facility [Herfurth F et al. 2015 Phys. Scr. 014065] via a beamline that features dedicated ion optics, non-destructive ion detectors, and a cryogenic fast-opening valve [Klimes J et al. 2023 Rev. Sci. Instr. 94 113202] which keeps the extreme vacuum of the trap stable while allowing access for ions and laser light. This beamline is constantly being upgraded towards efficient and well-controlled ion injection. We present the status and design updates of this beamline and the experiment.

## Poster Sessions / 95

### The HITRAP deceleration facility - heavy HCI at low energies

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The HITRAP facility, located at the GSI Helmholtzzentrum für Schwerionenforschung GmbH in Darmstadt, Germany, is designed to decelerate and cool heavy, highly charged ions (HCI) created by the GSI accelerator complex

1. The system consists of a two-stage linear decelerator, followed by a cryogenic Penning-Malmberg trap for subsequent ion cooling. The deceleration stages reduce the ion energy from 4 MeV/u to 500 keV/u and to 6 keV/u respectively, before forwarding a slow, but hot ion bunch towards the cooling trap. The trap is operated in a so-called nested configuration, in which the electrons, created by an external photo-electron source, are stored simultaneously with the HCI and serve as a cold thermal bath. After cooling, the ions can be transported via a low-energy transfer beamline towards various attached experiments [2]. A dedicated small ion source (Dresden EBIT) is attached to the beamline and used for commissioning of the cooling trap as well as a source of light HCI for attached experiments [3]. So far, deceleration of heavy HCI has been set up down to 6 keV/u, though the process is somewhat lengthy, hampered by a low delivery rate of a single ion bunch per 40 seconds. The subsequent electron cooling process is under development with promising results. Ions from the EBIT are regularly stored and mixed with electrons. Recently, the first indications of electron cooling of locally-produced HCI in a Penning trap could be achieved, a major milestone towards heavy HCI at eV and sub-eV energies. The current status of this development as well as future aspects will be presented.

1 Herfurth F et al 2015 Phys. Scr. 2015 014065

[2] Andelkovic Z et al 2015 Nucl. Instrum. Methods Phys. Res. Section A vol. 795 2015 055

[3] Sokolov A et al 2010 JINST 5 C11001

## Poster Sessions / 97

### High-resolution spectroscopy of fermium-255 at the RISIKO mass separator

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Studies of atomic spectra through resonant laser excitation and ionization provide information on nuclear structure. Precise measurements of the hyperfine structure (HFS) give an experimental insight on the nucleus' deformation through the electric quadrupole moments and the single-particle structure through the magnetic dipole moments. However, this method is limited by low production yields and scarce knowledge on the atomic structure [1]. Nevertheless, the measurements of these observable will help to further probe the transition to the macroscopic regime and to calibrate existing nuclear models of heavy nuclei.

This work will discuss the results of our last measurement campaign, where a sample of <sup>254</sup>Es was provided by the Florida State University and the Oak Ridge National Laboratory, USA. This sample was then neutron irradiated in the high-flux research reactor at the Institut Laue-Langevin in Grenoble, France, to obtain <sup>255</sup>Es. After the irradiation, the sample underwent a chemical separation at the Department of Chemistry –TRIGA site at Mainz University, Germany, allowing an iterative separation of the decay daughter <sup>255</sup>Fm.

This process delivered nine samples consisting of 10<sup>8</sup> to 10<sup>9</sup> atoms, used to study the atomic and nuclear structure of <sup>255</sup>Fm ( $Z = 100$ ) at the RISIKO Mass Separator at Mainz University.

High-resolution spectroscopy was performed using the Perpendicularly Illuminated Laser Ion Source and Trap (PI-LIST) together with an injection-locked Ti:sa laser system. Using two-step excitation schemes, the HFS in the ground-state transitions to the atomic levels at  $25099.8 \pm 0.2 \text{ cm}^{-1}$  and at  $25111.8 \pm 0.2 \text{ cm}^{-1}$  [2] were measured and the hyperfine coupling constants of these levels were determined.

- 1 M. Block, et al., Recent progress in laser spectroscopy of the actinides. *Progress in Particle and Nuclear Physics* 116, 103,834 (2021)  
 [2] H. Backe, et al., Laser spectroscopic investigation of the element fermium ( $Z = 100$ ). *Hyperfine interactions* 162(1-4), 3–14 (2005)

## Poster Sessions / 101

### RAPTOR –commissioning a collinear RIS device at the IGISOL

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Resonance ionization spectroscopy And Purification Traps for Optimized spectRoscopy (RAPTOR) 1 project is an experimental setup at the IGISOL facility in the Accelerator Laboratory of the University of Jyväskylä. RAPTOR combines the two most common methods for laser spectroscopy used at radioactive ion beam facilities: collinear laser spectroscopy and in-source laser-resonance ionization spectroscopy. Exploitation of the high selectivity of resonance laser ionization, the high efficiency of ion detection, and the high resolution achieved via fast beams, has proven to be a fruitful combination for optical spectroscopy. This technique, collinear resonance ionization spectroscopy (CRIS) [2], was pioneered in the past decade at the ISOLDE facility at CERN.

While the conventional collinear laser spectroscopy and CRIS methods exploit the kinematic compression of Doppler-broadening effects with beam energies of 30-60 keV, the RAPTOR device employs lower beam energies of 2-10 keV. Although this leads to lower spectral resolution, it improves the efficiency and selectivity of the charge-exchange process. Thus, measurements requiring high efficiency, particularly complex d and f atomic shell systems and refractory isotopes, are uniquely suitable for RAPTOR. In addition to laser spectroscopy, RAPTOR will provide isomerically purified ion beams to the JYFLTRAP double Penning trap - allowing high-precision mass measurements of states independent of energy separation, and post-trap assisted spectroscopy.

This contribution presents the status of RAPTOR, along with a recent redesign of the beamline and ion optical simulations. The commissioning results will be presented and compared to CRIS spectral linewidths and efficiencies.

- 1 S. Kujanpää et al., “RAPTOR: a new collinear laser ionization spectroscopy and laser-radiofrequency double-resonance experiment at the IGISOL facility”, *NIM B*, 541 (2023) 388-391  
 [2] A. Vernon et al., “Optimising the Collinear Resonance Ionisation Spectroscopy (CRIS) experiment at CERN-ISOLDE”, *NIM B*, 463 (2019)

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### Searching for new physics at short distances with optically levitated microspheres

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New phenomena emerging at the micron scale are common in extensions of the Standard Model and efforts to unify gravity with quantum mechanics. Interactions of this kind are typically parameterized by adding a Yukawa potential to the gravitational field. Our group searches for Yukawa-modified gravity using optically-trapped silica microspheres as force sensors, in contrast to the variants of mechanical springs used by other experiments. Previously, we reported the first constraints on modifications to Newtonian gravity using a levitated test mass of dimensions comparable to the scale of the Yukawa interaction, though the sensitivity was limited by backgrounds. In this talk, I will outline efforts to identify and mitigate the observed backgrounds and discuss how these improvements will enable a future run capable of probing unexplored parameter space.

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## Towards absolute nuclear charge radius measurements of Ag isotopes

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Nuclear charge radii of silver isotopes have been extensively investigated using laser spectroscopy [1,2,3]. However, the dependence of this method on large-scale atomic calculations for mass and field shift determination introduces significant systematic uncertainties that dominate the uncertainty of the extracted radii. Deviations with nuclear density functional theory [1,3] further emphasize the necessity for precise investigation of the mass and field shift for silver. Experimental determination is planned to be performed by employing muonic x-ray spectroscopy on <sup>107</sup>Ag, <sup>109</sup>Ag and <sup>108m</sup>Ag (longest-lived radio-isotope of Ag, half-life = 483 years).

The absolute charge radius of at least three silver isotopes is imperative for experimental determination of the mass and field shift.

While <sup>107</sup>Ag and <sup>109</sup>Ag can be readily enriched in large amounts, <sup>108m</sup>Ag requires a more intricate approach and can only be produced in microscopic quantities.

Nonetheless, advancements in the muonic x-ray spectroscopy method have enabled the treatment of targets down to  $5\ \mu\text{g}$  [4].

In this contribution, we report on the preliminary measurements performed at the Paul Scherrer Institute in October 2023.

Furthermore, we outline the progress made in producing the  $^{108\text{m}}\text{Ag}$  target, including insights from a proof-of-concepts experiment conducted at CERN-ISOLDE in November 2023.

1 M. Reponen, R.P. de Groote, et al. Evidence of a sudden increase in the nuclear size of proton-rich silver-96. *Nature Communications*, 12(1):4596, 2021.

[2] R. Ferrer et al. In-gas-cell laser ionization spectroscopy in the vicinity of  $^{100}\text{Sn}$ : Magnetic moments and mean-square charge radii of  $N=50$ – $54$  Ag. *Physics Letters B*, 728:191–197, 2014.

[3] R. de Groote. Collinear resonance ionization spectroscopy of silver between  $N=50$  and  $N=82$ . Technical report, 2020.

proposal number: INTC-P-551, experiment number: IS660, <http://cds.cern.ch/record/2752917?ln=en>.

[4] A. Adamczak et al. Muonic atom spectroscopy with microgram target material. *The European Physical Journal A*, 59(2):15, 2023.

## Poster Sessions / 116

# Commissioning a Laser Ablation Ion Source for TITAN Mass Spectroscopy

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The use of a Laser Ablation Ion Source (LAS) can bring a lot of flexibility and opportunity to mass-spectrometry experiments through the ability to produce a large diversity of ion species compared to other common ion sources. Of particular interest for trap-based mass-spectrometry applications is the potential to produce isobaric calibrants across a wide range of masses or of a specific species. To this end, a LAS is being developed for TRIUMF's Ion Trap for Atomic and Nuclear Science (TITAN)'s platform. TITAN consists of a suite of four ion traps, an RF Quadrupole cooler-buncher (RFQ) Multiple-Reflection Time-of-Flight Mass Spectrometer (MRTOF-MS), an Electron Beam Ion Trap (EBIT) and a Penning trap used for high-precision mass measurements. Having a LAS will benefit all the traps on the platform by providing mass calibrants for on-line experiments with radioactive beams and as a source for off-line experiments and technical development of the traps. The source will use computer-controlled mirrors to move the laser spot across the target and dynamic ion steering adjustments to allow for ionization of multiple species, studies of multiple samples on a single target, and the flexibility to continue developing novel ion target designs and methods. The LAS design has been optimized using SIMION simulations and will be commissioned at the University of Calgary before eventual installation on TITAN. The status of the commissioning will be discussed including characterization of capabilities such as ion species selectivity, ion current and transport efficiency. The addition of this source to TITAN will not only improve the precision of the mass measurements TITAN is built for but also provide opportunities to leverage the TITAN infrastructure and expertise for off-line experiments in diverse fields of research such as medical and environmental studies.

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**A Sr-90 Resonance Ionization and Ion Trap-laser Cooling Spectroscopy with Enhanced Detection Efficiency****Authors:** CHAO ZHANG<sup>None</sup>; Ryohei TERABAYASHI<sup>1</sup>; Shuichi HASEGAWA<sup>1</sup><sup>1</sup> *The University of Tokyo***Corresponding Authors:** hasegawa@tokai.t.u-tokyo.ac.jp, zhang-chao345@g.ecc.u-tokyo.ac.jp, terabayashi@tokai.t.u-tokyo.ac.jp

Sr-90 is an unstable (half-life = 28.9 a) decay product of fissile isotopes such as Pu-239 and U-235. The TEPCO Fukushima Daiichi Nuclear Power Plant accident released an estimated  $1\text{--}2.2 \times 10^{14}$  Bq Sr-90 to the ocean and  $0.1\text{--}1.4 \times 10^{11}$  Bq Sr-90 to the atmosphere. Sr proxies Ca in the food chain and is deposited in Ca-bearing tissues, especially bone, with a biological turnover of 18 years in adult humans. Sr-90 decays through beta-decay (up to 546 keV) which causes severe long-term internal exposure.

This study aims to investigate a novel trace analysis method for Sr-90, namely Ion Trap-Laser Cooling Spectroscopy (ITLCS), combining three-stage laser resonance ionization, quadrupole mass spectrometry, and ion trap for highly selective detection of Sr isotopes. Additionally, a newly designed ion guide is utilized to enhance ion transportation efficiency, enabling high-precision quantification analysis of Sr-90. The schematic of the ITLCS can be separated into ion source, ion filter, ion guide and ion trap correspondingly.

For the ion source part, the three-stage laser resonance ionization  $5s^2 1S_0 \rightarrow 5s5p 1P_1^{\circ} \rightarrow 4d^2 1D_2 \rightarrow 4dnp$  or  $4dnf$  has been investigated on the isotope shift and Stark shift to figure out the feasibility of resonance ionization Sr isotopes. For the ion guide part, an ion guide system with the conical octupole ion guides and the helium buffer has been applied to transport the generated and selected Sr ions moderately from the ion filter to the ion trap.

These advancements have potential applications in environmental monitoring and nuclear safety, offering precise and sensitive Sr-90 analysis. Overall, the study contributes theoretically and practically to analytical methodologies and instrumentation.

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**Collinear laser spectroscopy at RAON:Progress and perspectives of CLaSsy****Authors:** Chaeyoung Lim<sup>1</sup>; Cheolmin HAM<sup>2</sup>; Dong Geon KIM<sup>2</sup>; Donghyun KWAK<sup>3</sup>; Eun San KIM<sup>4</sup>; Jens LASSEN<sup>5</sup>; Jung Bog KIM<sup>6</sup>; Kyoungho TSHOO<sup>2</sup>; SEONGJAE PYEUN<sup>2</sup>; Taeksu SHIN<sup>2</sup>**Co-author:** Sung Jong Park <sup>2</sup><sup>1</sup> *Institute for Rare Isotope Science(IRIS),IBS / Department of Accelerator Science,Korea University*<sup>2</sup> *Institute for Rare Isotope Science*<sup>3</sup> *Institute for Rare Isotope Science/UNIST*<sup>4</sup> *Korea University*<sup>5</sup> *TRIUMF*<sup>6</sup> *Korea National University of Education***Corresponding Authors:** sjpark@ibs.re.kr, cylim@ibs.re.kr

CLaSsy is an experimental setup designed for laser spectroscopy on radioactive isotopes at the RAON ISOL facility in the Institute for Rare Isotope Science (IRIS), Korea. Laser spectroscopic technique provides the model-independent determinations of nuclear ground state properties, such as the mean-square charge radii and the electromagnetic moments. We have successfully installed the CLaSsy beamline and tested a charge exchange cell using an offline ion source connected to the beamline. Currently, we focus on the set-up of the frequency-tunable laser system and the laser beam transport system, along with the optical detection system on the CLaSsy beamline. The current effort aims at

the first laser spectroscopy experiment on the radioactive isotopes, such as Na and Al, produced at the RAON ISOL facility.

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## Towards Measurements of Electroweak Nuclear Properties using Single Molecular Ions in a Penning Trap

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We present the development of a novel Penning ion trap for precision spectroscopy of symmetry-violating electroweak properties using single trapped molecular ions [1]. The high magnetic field of the Penning trap can be used to Zeeman shift two molecular states of opposite parity to near degeneracy, enhancing the sensitivity of parity-violating nuclear properties by more than 11 orders of magnitude [2]. Hence, our proposed experimental setup is expected to provide highly sensitive measurements of symmetry violating nuclear properties across the nuclear chart. This contribution will describe the status of a cryogenic Penning trap for performing measurements in SiO<sup>+</sup> and TlF<sup>+</sup> molecules, as well as discuss future prospects of this technique.

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Poster Sessions / 112

## Resonance ionization spectroscopy of Nd for isotope micro-imaging of particles

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The isotopic composition of Nd is used in a wide range of nuclear field, such as forensic analysis and fuel burnup evaluation, and the currently most used analytical methods include TIMS and ICP-MS.

However, the analytical samples obtained in decommissioning of Fukushima's failed reactors contain a mixture of particles of different sources, and these bulk analytical techniques which cannot distinguish individual particles lose the information on their origin and history. Conversely, if the origin can be determined from the burnup of each particle, it is of great importance for clarifying accident progress and criticality safety assessment. For this reason, we have applied ion sputter mass spectrometry imaging, which can measure the distribution of nuclides in individual particles, and have developed laser resonance secondary neutral mass spectrometry as a countermeasure against the isobaric interference. In this study, we performed two-step ionization spectroscopy to obtain highly efficient ionization schemes of Nd. As a result, we identified more than 120 even-parity autoionizing levels and their candidate J-values. The analysis of the observed autoionizing Rydberg series yielded a value of  $44560.1 \pm 0.5 \text{ cm}^{-1}$  as a more accurate ionization potential of Nd. The saturation method was used to measure the transition cross-sections for some intense ionization transitions. From the measured cross-sections, the ionization efficiencies of some two-step ionization schemes were evaluated using the scheme cross-section formula to obtain several promising schemes with higher ionization efficiency than previously reported one.

## Poster Sessions / 113

### A new community hub for collecting resonance ionization schemes and associated tools

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The "RILIS database", established in 2011, has served as a central hub for resonance ionization schemes for the laser spectroscopy community. Recently, data protection has required us to move it behind CERN's single sign-on, hampering community access. To re-establish a database accessible to all, we have created a new website and community hub 1 to share collected resonance ionization schemes.

The database will, in its first version, consist of the previous CERN RILIS database entries and additional schemes from our individual collections. To simplify scheme searching, an overview of the periodic table with clickable element names and overview pages for each element of interest are provided.

The website is hosted on GitHub pages, making it possible for everyone to contribute in a simple and streamlined manner. When new scheme files are added, the page is automatically built and deployed via GitHub Actions [2] using the MkDocs framework [3] and our own Python routines. Database files are stored in an easy-to-read json [4] format, simplifying creation of new schemes. Resonance ionization schemes are automatically drawn using the RIMSSchemeDrawer software [5], generating a unified look which can be used for publications and presentations. Administrator approval ensures that submissions are checked before publication on the website.

The new website will serve as a community hub for laser resonance ionization schemes and associated tools (e.g. Doppler-broadening effects, frequency mixing angles, ...). Tools can, for example, be bound into the site using web-applets, or can be linked to directly from the site. The project is intended to be a community-driven effort and will thus rely on input from all laser spectroscopists. The simple interface combined with tooling hosted on GitHub provides ample room for growth. We are looking forward to your ideas, contributions, etc.

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[3] <https://www.mkdocs.org/>

[4] <https://en.wikipedia.org/wiki/JSON>

[5] <https://github.com/RIMS-Code/RIMSSchemeDrawer>

## Poster Sessions / 135

### An Upgraded Hot-Cavity Catcher for In-Source Laser Spectroscopy of Neutron-Deficient Pd Isotopes

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Investigating the neutron-deficient isotopes of palladium (Pd, Z=46), positioned close to the doubly magic nucleus <sup>100</sup>Sn (N=Z=50), provides valuable information on the neutron-proton interaction, residual forces and serves as a crucial benchmark for nuclear models 1.

Laser spectroscopy is a powerful tool for studying ground and isomeric state properties in nuclei, such as mean-square charge radii and nuclear moments in a model-independent way. <sup>98</sup>Pd represents the most neutron-deficient isotope within the palladium isotopic chain examined thus far through collinear laser spectroscopy [2].

The hot-cavity catcher proves to be more efficient in reaching the lighter and more exotic isotopes than <sup>98</sup>Pd. Using a similar technique, promising results have been achieved in the optical measurements of neutron-deficient Ag isotopes crossing the N=50 magic number [3]. An upgraded design of hot cavity catcher was tested recently. A primary beam of <sup>107</sup>Ag<sup>20+</sup> from the K130 cyclotron was implanted into a graphite catcher. Following the implantation atoms diffuse out and effuse into the glassy carbon transfer tube where the atoms are resonantly ionised using a three-step excitation scheme. The ions are then accelerated to 30 keV and mass separated using a dipole magnet. The ion extraction time was measured for different temperatures of the cavity and the mean value was determined to be around 25 ms. An overall efficiency of around 10% was observed.

Similar efficiency can be expected for Pd isotopes with the current hot-cavity and extraction parameters. This could make the feasibility of studying Pd isotopes using in-source laser spectroscopy technique all the way to <sup>92</sup>Pd (N=Z).

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3. Reponen, M. et al. Nature Communications 12, 4596 (2021).

## Poster Sessions / 117

### Development of an accelerator-driven ion source for barium tagging in nEXO

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Neutrinoless double-beta decay ( $0\nu\beta\beta$ ) offers a way to probe for physics beyond the Standard Model. Observation of  $0\nu\beta\beta$  would validate the Majorana nature of neutrinos, demonstrate violation of lepton number, and help explain the observed baryon asymmetry in the universe. In addition,  $0\nu\beta\beta$  could also shed light on new mass generation mechanisms up to the GUT scale. The proposed nEXO experiment will search for  $0\nu\beta\beta$  decay in  $^{136}\text{Xe}$  with a projected half-life sensitivity exceeding  $10^{28}$  years at 90% confidence level, using a time projection chamber filled with 5 tonnes of liquid xenon (LXe) enriched to  $\sim 90\%$   $^{136}\text{Xe}$ . In parallel, different approaches are being investigated within the nEXO collaboration to further suppress backgrounds in the region of the  $0\nu\beta\beta$  signal. One such technique is called barium (Ba) tagging, which involves extracting and identifying the  $\beta\beta$ -decay daughter Ba ion. Ba tagging will ensure an irrefutable classification of each  $\beta\beta$  event and further increase the experimental sensitivity of nEXO. To test and optimize the tagging techniques, an accelerator-driven ion source is currently being developed. Radioactive ions from TRIUMF's Isotope Separator and Accelerator (ISAC) facility will be implanted in a LXe volume, extracted electrostatically, and detected using  $\gamma$  spectroscopy. The motivation and overview of Ba tagging, and details of the ion source apparatus, development status and planned experiments will be presented.

## Poster Sessions / 123

### Evaluation of gadolinium ion emission characteristics in aqueous solution using laser-induced luminescence spectroscopy

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Gadolinium (Gd) is a rare earth metal belonging to the lanthanide series. Taking advantage of its large neutron absorption cross section and high  $\gamma$ -ray energy ( $\sim 8$  MeV in total) of  $(n, \gamma)$  reaction, Gd sulfate is dissolved in the Super-Kamiokande (SK) 50 kton water Cherenkov detector, which is being carried out as the SK-Gd project, to increase the detection sensitivity of supernova relic neutrino events.

In this work, the emission characteristics of  $\text{Gd}^{3+}$  ions in aqueous solution such as quenching by anions and excitation spectra are studied using laser-induced luminescence spectroscopy. A simulation study is performed to estimate the  $\text{Gd}^{3+}$  emission background rate from cosmic muons in the SK-Gd experiment. We are developing a portable monitoring system based on this spectroscopic technique to enable real-time measurements of  $\text{Gd}^{3+}$  concentration and emission lifetime without contamination during water sampling.

## Poster Sessions / 124

### Status of the MR-ToF MS for JetRIS for laser spectroscopy of heavy actinides at GSI/HIM

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The in gas-Jet Resonance Ionization Spectroscopy (JetRIS) apparatus is applied for laser spectroscopy of isotopes in the heavy actinide region to determine their atomic and nuclear properties, at GSI, Darmstadt, Germany. So far, JetRIS utilizes  $\alpha$ -decay detection to maximize sensitivity while minimizing the background from unwanted ions. However, for long-lived nuclides ( $t_{\frac{1}{2}}$  *gt* *approx* 10 h) decay-based detection will not be practical. Therefore, a multi-reflection time-of-flight mass separator (MR-ToF MS) will be added to the JetRIS apparatus, allowing for a separation of ions by their mass-to-charge ratios with a high mass-resolving power and efficiency. This will open up the possibility of mass-selective ion detection with low background and will also enable the measurement of non  $\alpha$ -decaying species, as well as long-lived and stable isotopes. The MR-ToF MS design is developed within the Darmstadt's MR-ToF (Da's MR-ToF) Collaboration and an overview on the setup and its integration into JetRIS will be given. The status of the commissioning, as well as experimental results and prospects for future measurements will be discussed.

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### Towards an all-solid state OPO/OPA system for high-resolution laser spectroscopy.

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Studies of the atomic spectrum through resonant laser excitation provide access to nuclear structures. Precise measurements of the interactions of the nuclear ground state with the electronic shell permit the extraction of nuclear properties which are closely related to the nucleus' configuration and shape. With atomic transitions in the range of a few eV, these are accessible with lasers.

For high-resolution laser spectroscopy, the optical linewidth must be low enough to resolve the atomic lines up to the hyperfine structure but not much narrower than the resolution-limiting effect of the specific experimental setup to maximize the efficiency. Depending on the spectroscopy technique in use, resonance peak linewidths can be as low as 40 MHz. At the cost of challenging experimental setups, pulsed laser light with optical linewidths lower than 50 MHz have been reported<sup>1</sup> by the amplification of a cw-dye in a pulsed dye amplifier (PDA) and of 20 MHz<sup>[2]</sup> by injection-locking a titanium:sapphire (Ti:Sa) with a narrow-linewidth cw-Ti:Sa. On the other hand, an optical parametric oscillator (OPO) seeded PDA system has demonstrated<sup>[3]</sup> comparable performance in the range near 330 nm, with a linewidth close to 100 MHz.

As more exotic nuclides are accessible, new laser techniques are needed to produce wavelengths in notoriously challenging ranges, whilst maintaining power stability and optical narrow-band operation. In this context, we propose an all-solid-state system based on an OPO seeded optical parametric amplifier (OPA) to generate narrow-band, high-energy pulses for high-resolution laser ionization



spectroscopy, in the range of 1000–1530 nm to be subsequently frequency doubled or tripled, to obtain the desired experimental wavelength. In this preliminary characterization, pulse length and optical linewidth are measured to match the specific experimental requirements.

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## Poster Sessions / 126

### Resonance Ionization Mass Spectrometry by Switching Fundamental/SHG Operation of Ti:Sapphire Laser toward Multi-element Isotopic Analysis

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In the decommissioning of the Fukushima Daiichi Nuclear Power Plant, a wide variety of samples containing fission products, nuclear fuel materials, actinide nuclides, and other materials are required to be analyzed. Resonance ionization mass spectrometry is suitable for the isotope analysis of such complex samples because it does not suffer from isobaric interference. For efficient resonance ionization, a scheme combining the fundamental and second harmonic generation (SHG) of Ti:Sapphire laser systems should be adopted. We developed a modified grating-type Ti:Sapphire laser that can instantly switch between fundamental and SHG operation modes, named mode switching Ti:Sapphire laser. Rapid changeover of Cs/Sr resonant ionization using two sets of the mode switching Ti:Sapphire laser with a beam path combination system was demonstrated. The characteristics of the laser and its application to Sr isotope ratio analysis will be presented.

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## Poster Sessions / 127

### Simulation-aided offline optimization of the JetRIS apparatus

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Laser spectroscopy experiments are an important tool for nuclear structure studies, providing nuclear-model independent observables that serve as anchor points for theoretical models. For the super-heavy elements ( $Z \geq 104$ ), where stability is enhanced by shell effects, laser spectroscopy allows for detailed investigations of such nuclear observables as charge radii, nuclear moments and spin. And the technique's high efficiency and sensitivity make it possible to work with atom-at-a-time production rates, characteristic for this region of the nuclide chart.

JetRIS[2,3] is an in-gas-jet resonant ionization spectroscopy setup, which accepts a high-energy beam of radioactive ions, neutralizes and re-ionizes them in a hyper-sonic gas jet with high resolution (approx. 200 MHz in the actinide region[4]), allowing for the production of isotopically and isomerically pure beams[5]. Inside the gas cell, reaction products are guided with DC electric fields towards a heated filament. The collected ions are promptly re-evaporated as neutrals close to the nozzle throat, achieving target-to-detector times well below 300 ms. Currently, in order to separate the signal from background, the detection stage is comprised by a silicon detector[6], however, a modification of the system to include a Multi-Reflection Time-of-Flight (MRToF) stage for mass-selected ion detection is planned, which will expand the range of isotopes available for study beyond alpha-emitters with suitably short lifetimes.

In this talk, we report on the results obtained in the 2022 beamtime[7] and the following offline optimization performed with the aim to improve the system's efficiency. Already implemented modifications and their effects on the measured extraction time and efficiency using an offline radioactive recoil ion source are compared to the results of detailed COMSOL Multiphysics simulations of JetRIS. The numerical model provides a deeper insight into the setup's operation, guiding further developments and highlighting potential pitfalls during online operation.

## Poster Sessions / 130

**Study of interference effects in optical spectroscopy****Author:** Anita Candiello<sup>1</sup>**Co-authors:** Phillip Imgram<sup>2</sup>; Pierre Lassegues<sup>2</sup>; Ruben de Groot<sup>3</sup><sup>1</sup> *KU Leuven*<sup>2</sup> *KU Leuven (BE)*<sup>3</sup> *Instituut voor Kern- en Stralingsfysica, KU Leuven, Leuven, Belgium***Corresponding Authors:** anita.candiello@kuleuven.be, phillip.imgram@kuleuven.be, pierre.lassegues@cern.ch, ruben.degroot@kuleuven.be

The study of the nuclear properties allows to deeply investigate the nuclear structure and the nucleon-nucleon interaction. Specifically, the nuclear electromagnetic moments give an indication of the charge and current distribution in the nucleus. Measurements of these properties can be obtained with laser spectroscopy, an experimental method which probes the hyperfine structure of atoms.

An effect that can influence fluorescence spectroscopy measurements is quantum interference. If not accounted for, it produces a systematic error in determining properties of nuclei. It is therefore important to take it into consideration.

This effect has been observed and investigated in Cd and Zn isotopes ([1,2]), furthermore illustrating the link between the observed spectrum shapes and the laser polarization angle. To study the polarization effect, we performed laser spectroscopy measurements and recorded fluorescence spectra of Sr isotopes with different polarization angles.

Measurements on different isotopes have in the past been performed without taking into account the interference effect. This is for example the case of Na ([3]) and Cs ([4]). While Na presents rather small splittings among the hfs transitions, the hfs of cesium presents large splittings, thus the interference effect is expected to be smaller. However, the extremely small reported uncertainty ( $\leq 2$  kHz), may nevertheless require careful consideration. Also, Cs spectroscopy yielded a value for the nuclear magnetic octupole moment, which is larger than can be accounted for by nuclear theory. It is therefore important to investigate the accuracy of those measurements carefully.

Motivated by the scientific cases listed above, we designed an atomic beam unit, which I report on here, alongside recent laser spectroscopy measurements on Sr and Na. The aim of these measurements is to benchmark the interference effect in sodium and to calculate the effect that we would expect in cesium.

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[3]Gangrsky, EPJA3.313-318

[4]Gerginov, PRL97.7

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**Status of the Fast Radioactive Ion Extraction and Neutralization Device for S3 (FRIENDS3)****Author:** Elodie MORIN<sup>1</sup>**Co-authors:** David Lunney<sup>1</sup>; Enrique Minaya Ramirez<sup>1</sup>; Samuel Roset<sup>1</sup>; Serge Franchoo<sup>1</sup>; Thierry Hourat<sup>1</sup>; Vladimir Manea<sup>1</sup>; Wenling Dong<sup>1</sup><sup>1</sup> *IJCLab*

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SPIRAL2 facility located at GANIL in Caen has recently been commissioned. Combined with the Super Separator Spectrometer ( $S^3$ ), which is currently being prepared for commissioning, it will be able to produce high intensity beams of neutron-deficient isotopes close to the proton dripline. Ions produced by SPIRAL2/ $S^3$  will be studied with the experimental setup  $S^3$  Low Energy Branch ( $S^3$ -LEB) [2, 3, 4] which is currently being installed at the focal plane of  $S^3$ . The ions will be first thermalized in a gas stopping cell and then guided out by the gas flow, neutralized and extracted in a supersonic gas-jet. The extracted species will then be studied using laser spectroscopy, mass spectrometry and decay spectroscopy.

The current  $S^3$ -LEB gas cell extraction time is on the order of a few hundred milliseconds. Thus, the most short-lived isotopes will be lost before being extracted. In order to improve the  $S^3$ -LEB gas cell, a test bench was designed at IJCLab in Orsay within the scope of FRIENDS $^3$  project [5]. This test bench will be dedicated to the development of a fast extraction gas cell as well as an improvement of the neutralization techniques in order to enable nuclear structure studies on the most short-lived isotopes.

The present contribution will focus on the simulations, design and construction of the new setup as well as the first tests performed with it and also with a simplified version operated during the design process.

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## Diamond-based Raman laser technology for RILIS operation and high-resolution spectroscopy

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The Raman nonlinear process consists in a scattering interaction between light and a crystal. Through the process, a photon loses energy to a phonon of the crystal, leading to an up-shift in the laser wavelength. This wavelength shift can be used to extend the laser frequency coverage of the RILIS laser systems, for operation and high-resolution spectroscopy experiments.

During the past years, different Raman laser designs have been developed, characterized, and tested for resonant ionization.

Particularly, a Z-fold diamond laser resonator, conserving the pump laser's linewidth, has been implemented, making it suitable for regular RILIS operation. Recently, the use of this design has been

validated in MEDICIS with the ionization of Radium, for which the first step frequency of the laser scheme (482nm) is difficult to achieve using an intra-cavity doubled TiSa lasers.

A different design based on a monolithic diamond Raman resonator, provides narrow linewidth, suitable for high-resolution spectroscopy, for example with PI-LIST. The characterization of the first and second Stokes output, emitted by such Raman laser, has been performed. The measured efficiency (up to 40%), linewidth (down to 150MHz) and tunability well satisfy the requirements for high-resolution spectroscopy experiments.

The design of both types of diamond Raman lasers, alongside performances characteristics will be presented, as well as the preliminary results of applications for ion beam production and high-resolution spectroscopy.

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### PI-LIST technical developments at CERN

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Laser resonance ionization spectroscopy in the ion source coupled to the isotope production target is proven to be a highly sensitive tool for nuclear structure investigations on isotopes with low production and extraction yields [1]. While the efficiency of this technique is unrivalled, the spectral resolution is ultimately limited by Doppler broadening. At the ion source temperature of ~2000 °C typically required for efficient operation, Doppler broadening results in a 1-10 GHz experimental resolution limit whereas precise measurements of nuclear magnetic and quadrupole moments often require resolving hyperfine structure splittings.

A new laser ion source design has been implemented at ISOLDE recently to provide in-source spectroscopy capabilities down to experimental linewidths of 100 –200 MHz. It is based on the high beam purity Laser Ion Source and Trap [2, 3], featuring spatial separation of the hot cavity where potential ion beam contamination can arise from non-laser related ionization mechanisms such as surface ionization, and a clean laser-atom interaction region in an RFQ unit directly downstream, where solely element-selective laser ionization takes place. In the Perpendicularly Illuminated LIST (PI-LIST) [4], a crossed laser/atom beam geometry reduces the Doppler broadening by addressing the transversal velocity components of the effusing atom ensemble.

The applicability of this technique to ISOL facilities in general, its limits especially in terms of significant efficiency loss, and technical implementation challenges are discussed.

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## Poster Sessions / 138

### Stopping and Trapping of Radioactive Isotopes for Precision Experiments (STRIPE)

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The investigation of nuclear ground-state properties of short-lived radioactive isotopes through laser spectroscopy is an important probe of state-of-the-art nuclear-structure theories. This field has mainly been driven by Collinear Laser Spectroscopy (CLS) and Resonant Ionization Spectroscopy (RIS) in the last decades. In both techniques, the laser spectroscopy is performed in-flight which limits the interaction time between the laser and atoms to few  $\mu\text{s}$ . This inherently results in linewidths larger than few MHz. To increase the interaction time and with it the possible observable linewidth by orders of magnitude, a new quest has started with the goal to stop and trap radioactive isotopes for precision experiments (STRIPE). In contrast to commonly used buffer-gas filled linear Paul traps, this approach will try to circumvent the buffer gas and laser-cool the decelerated ions inside the Paul trap instead. This will enable high-precision measurements of the nuclear hyperfine structure through laser spectroscopic double-resonance experiments to investigate nuclear octupole moments. Furthermore, weak optical transitions with narrow linewidths will be explored which might open the route for investigations of King plot nonlinearities over long isotope chains. To characterize and optimize this process, a new offline beamline is currently under construction at the Institute for Nuclear and Radiation Physics of KU Leuven. This contribution will give an overview of the project and present the current status.

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## Observation of rovibrational transitions of strontium oxide isotopologues based on cavity ringdown spectroscopy

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Cavity ringdown spectroscopy (CRDS) is one of the most sensitive laser absorption spectroscopic techniques employing a highly reflective resonator. We have proposed to apply CRDS to the observation of rovibrational transitions of strontium oxide and its isotopologue, particularly toward the detection/measurement of radiative molecules such as  $^{90}\text{SrO}$ . Experimental details as well as the observed stable SrO isotope spectra will be shown in the presentation.

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## Absolute ion beam current quantification at the RISIKO mass separator for ionization efficiency determination

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Faraday cups (FCs) are well-known tools for ion beam current measurements via integration of the accumulated electric charge but also support further applications in charge particle analysis, e.g., in space or for fusion plasma surveillance. They provide an easy and robust way to quantitatively determine currents of different types of ion beams from the fA range up to Amperes for a variety of applications in mass spectrometry, particle accelerators, and others. At the RISIKO mass separator of Johannes Gutenberg University in Mainz a multitude of stable and radioactive isotopes are studied, which are selectively ionized via resonant laser ionization, accelerated with energies around 30 keV, mass-separated for further beam purification in a sector field magnet and afterward traced or collected for further use. In all cases, accurate quantification from precisely counting individual ions by secondary electron multipliers (below 10 pA, corresponding to  $10^7$  particles per second) up to recording ion currents on the different FCs along the beam path (above 1 pA) must be guaranteed. An obstacle is the sputtering of electrons and ions from the collection target of the FC, which obscures the results and cannot easily be fully suppressed by suitable repeller electrodes in the device. Comparative measurements using  $\alpha$ -spectroscopy on the radioisotope  $^{177g}\text{Lu}$  indicated a systematic underestimation of the ion beam current measurements of the FCs at RISIKO. Therefore, a new FC design with a conical-shaped target area was developed and installed. Characterization measurements with this optimized design agreed to the  $\alpha$ -spectroscopy, demonstrating an absolute quantification of ion currents in the range from 10 pA to 100 nA with a precision of about 1 %. Meanwhile, this work was extended to cover the entire range of accessible atomic masses from  $A = 20$  up to heavy actinides, which is most relevant for efficiency determination and ion implantation.

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### Nuclear Charge Radii of Silicon Isotopes

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The nuclear charge radius of  $^{32}\text{Si}$  was determined from isotope-shift measurements performed at the collinear laser spectroscopy setup BECOLA at the Facility for Rare Isotope Beams (FRIB, Michigan State University). The extracted charge radius was compared to ab initio nuclear lattice effective field theory, valence-space in-medium similarity renormalization group and mean field calculations.

Furthermore, the charge radius of  $^{32}\text{Si}$  completes the radii of the mirror pair  $^{32}\text{Ar}$ - $^{32}\text{Si}$ , whose difference was correlated to the slope  $\chi$  of the symmetry energy in the nuclear equation of state 1. We will present the experimental details including the production of a  $^{32}\text{SiO}$  beam in the batch mode ion source and molecular break-up at BECOLA as well as the results and their implications for nuclear structure and the nuclear equation of state.

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1 arXiv:2309.02037 [nucl-ex]

## Poster Sessions / 153

### Advancing Radiation Detected Resonance Ionization towards more exotic nuclei

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Experimental data on atomic and nuclear properties for exotic nuclei in the heavy actinide region ( $Z \geq 100$ ) remain scarce up to date. The Radiation Detected Resonance Ionization Spectroscopy (RADRIS) apparatus, located at GSI, Darmstadt, Germany, is employed to determine quantities, such as atomic energy levels, ionization potentials, nuclear moments, mean-square charge radii, and isotope shifts. Past measurements at RADRIS encompassed the investigation of  $^{245,246,248-250,254}\text{Fm}$  and  $^{251-255}\text{No}$ . In the current setup the detection of laser ions via their  $\alpha$ -decay for nuclei with half-lives in the order of several hours or longer becomes impractical. This presentation will show already obtained results with RADRIS and how future improvements will increase the methods reach towards longer-lived nuclei. This will allow accessing e.g.,  $^{246}\text{Cf}$  (35.7 h) and  $^{252}\text{Fm}$  (25.39 h). The latter is of interest, as it is located directly at the  $N = 152$  shell gap in the fermium isotopic sequence, thus providing the missing information between previously studied isotopes on the neutron-rich and on the neutron-deficient side.

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### Technical progress at the double Penning trap PIPERADE

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The inauguration of the buildings for the DESIR facility marked an essential step in developing experiments with low-energy radioactive beams in France. The LP2IB laboratory has been a primary driving force by devising several complex devices that will be the backbone of the facility. In this presentation, I will show the development work done for one of these devices, i.e. the double Penning trap PIPERADE (PIèges de PENning pour le RADionucléides à DESIR). This Penning trap spectrometer has been designed for high-resolution mass purification of strongly contaminated ion beams. To push the limits of existing devices, PIPERADE is equipped with a high-capacity large trap that aims to separate up to  $1e5$  ions per bunch. Purified samples will be re-injected in the main DESIR beam line for downstream setups to perform trap-assisted spectroscopy. Alternatively, the samples can be utilized to perform high-precision mass measurements. After a presentation of the DESIR facility and of the local installation at LP2I Bordeaux, I will present the PIPERADE device as well as the most recent developments on the trap, notably the progress on the PI-ICR technique.

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## Electromagnetic moments from angular momentum projected nuclear DFT

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The spontaneous symmetry breaking is one of the core elements in the nuclear density functional theory (DFT). It allows effectively to include various correlations on the wave-function, while still preserving the simplicity of the mean-field based description. Unfortunately, with broken symmetries, the obtained wave-function is no longer an eigenstate of corresponding symmetry group. For example, a deformed mean-field wave-function has no definite value for angular momentum. Therefore, it is not meaningful to compute certain observables, like the nuclear electromagnetic moments. To remedy this issue, broken symmetry needs to be restored with projection techniques.

This presentation describes the new angular momentum projection (AMP) implementation on the HFBTEMP computer code. The HFBTEMP code 1 solves the Hartree-Fock-Bogoliubov (HFB) equations in axial basis, without assuming time-reversal symmetry. This allows a proper treatment of various polarization effects in odd-A nuclei. After solving the HFB state, AMP is carried out to obtain various electromagnetic moments, among other observables. Implemented hybrid OpenMP+MPI

parallelization allows efficient use of supercomputing facilities. As a case study to benchmark the new implementation, calculated spectroscopic nuclear magnetic moments and magnetization distributions in potassium isotopic chain are discussed. These are connected to recent measurement of the differential hyperfine anomaly between 47K and 39K at ISOLDE, CERN [2]. In order to investigate this anomaly, various radial moments of M1 operator and spin-asymmetry operator have been calculated. The calculated radial moments of magnetization have much larger variation among potassium isotopes as compared to the magnetic dipole moments. This indicates that estimation of the Bohr-Weisskopf effect via simple uniformly magnetized sphere may not be sufficiently accurate. 1 M. Kortelainen, to be published (2024).

[2] M. L. Bissell, et al., in preparation (2024).

## Poster Sessions / 178

### High Accuracy Calculations of Properties of Heavy Atoms and Molecules

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Probing the properties of heavy atoms and molecules to ever greater accuracy provides ample opportunity for advancements in our understandings nuclear structure and to further extend the limits of atomic structure calculations [1-2]. In heavy atoms and molecules the role of relativistic and correlation effects are of great importance and their study adds to our understanding of these effects [3]. Numerical methods such as Fock space couple cluster, configuration interaction (CI) and CI combined with many-body perturbation theory are at the forefront of high accuracy atomic calculations. In this work calculations of properties of heavy atoms and molecules are carried out using highly accurate and relativistic numerical methods.

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### Laser spectroscopy offline studies at the GISELE-GANIL laboratory for preparation of the S3-LEB commissioning

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Some properties of the nuclear interaction manifest in the neutron deficient nuclei and in the heavy and super-heavy elements. Therefore, measurements of nuclear observables of these nuclei will serve to constrain available nuclear models. At GANIL-SPIRAL2, these nuclei will be produced with unprecedented yields, thanks to the combined action of the high intense primary beams delivered by the LINAC together with the Super Separator Spectrometer (S3) 1. The Low Energy Branch (S3-LEB) set-up will be located at the final focal plane of S3. This set up will allow to measure charge radii, nuclear moments, masses and decay properties simultaneously, of ground and long-lived isomeric states of the very exotic nuclei produced. The LEB set-up makes use of the In-Gas Laser Ionisation and Spectroscopy technique; the ions from S3 are stopped and neutralized in a gas cell for further extraction in a supersonic jet where the laser light interacts [2, 3, 4]. Afterwards, the ionized ions are sent to a MR-TOF-MS PILGRIM device [5] and a decay station. This contribution focuses on the laser work performed at the GISELE laboratory at GANIL. At GISELE, studies of the sensitivity of a given laser ionization scheme for extraction of the nuclear observables are performed, focusing on the first online experiments planned at S3-LEB. This contribution will describe the existing laser set-up installed at GISELE, the set-ups to be installed, the results obtained of laser scheme investigations of some elements and the forthcoming plans.

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# Stopping power of Coulomb crystals for precision measurements in antimatter and nuclear physics

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Laser Doppler cooling, a technique well-established since 1975, exploits laser light to cool atoms. When applied to trapped ions, this method leads to the formation of unique structures known as

Coulomb crystals. These organized and cooled ion clouds present promising prospects in spectroscopy, particularly for species inaccessible to laser Doppler cooling via sympathetic cooling. The extension of these techniques beyond atomic physics introduces new avenues for detecting, capturing, and cooling a diverse range of charged objects for precision measurements, encompassing antimatter, highly charged ions, macromolecules, and potentially radioactive ions.

In our ongoing research program ESPRIT (Exploring stopping power in ion traps), we investigate the interactions of various projectile ions through Coulomb crystals within radiofrequency traps, disturbing their thermal equilibrium. Within our experimental setup, GiantMol, a radiofrequency ion trap is utilized to produce laser-cooled calcium ion clouds. This setup is complemented by an external ion source capable of generating projectiles with varying mass and charge states. Additionally, specific ion optics are employed to ensure the precise separation and injection of ions into the radiofrequency trap. Through this configuration, our goal is to explore the feasibility of utilizing Coulomb crystals as detectors and potentially as capture media for heavy ions. These investigations present novel opportunities in nuclear physics, potentially enabling the cooling of radioactive ions to temperatures necessary for high-resolution laser spectroscopy or mass spectrometry. This abstract seeks to emphasize the transformative potential of laser Doppler cooling and sympathetic cooling in ion traps, with broad implications for advancing topics across various fields like antimatter physics, nuclear physics or even analytical chemistry

## Poster Sessions / 169

### Performance of the SHIPTRAP mass spectrometer

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Within the recent FAIR phase-0 program, the Penning-trap mass spectrometer SHIPTRAP at GSI in Darmstadt, Germany, was used to extend direct high-precision mass spectrometry to superheavy nuclides ( $Z \geq 104$ ) in the vicinity of the  $N=152$  shell closure 1.

In spite of challenging experimental conditions as long measurement times due to low production rates down to few atoms per hour, the improved efficiency, ion sensitivity and mass-resolving power allowed resolving metastable states with half-lives  $>200$  ms from their respective ground state in No ( $Z=102$ ), Lr ( $Z=103$ ) and Rf ( $Z=104$ ) isotopes. For the first time, isomer excitation energies in the range of  $\approx 30$  keV to 1.3 MeV were determined directly for these heavy nuclides. In addition, multiple metastable states in a variety of heavy isotopes, many of which are close to the  $Z=82$ ,  $N=126$  shell closures, have been measured, e.g., for isotopes of Pb, Bi, Po, At, Fr ( $Z=82-87$ ), and Cf ( $Z=98$ ). This allowed the direct determination of the excitation energies of long-lived isomeric states and therefore to contribute to the understanding of the level and decay schemes of these heavy nuclei, complementing the findings from decay and laser spectroscopy investigations.

This contribution focuses on the experimental challenges, the efficiency of the setup and the systematic uncertainties of the measurements.

1 O. Kaleja et al, Phys. Rev. C 106 054325 (2022)

## Poster Sessions / 176

### An electrostatic trap for high sensitivity, on-line laser spectroscopy

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Collinear laser spectroscopy coupled with optical pumping, within the cooler-buncher, has proved a highly successful technique at IGISOL-4 [1-3], facilitating spectroscopy on manganese, niobium, yttrium and even the doubly charged yttrium ion. The pumping, while highly efficient and well matched to our pulsed laser system, is subject to Doppler and pressure perturbations and collisional relaxation within the gas-filled device. These limitations motivated the development of a secondary electrostatic trap, operating in vacuum, and resulted in the development of the Manchester Cone-Trap.

The ConeTrap, pioneered by Schmidt et al. [4], is an electrostatic device that is especially suitable for deployment at the IGISOL [5]. The devices have been shown to successfully contain close to

$10^5$  ions for time periods exceeding 100 ms (many times the atomic excitation and de-excitation lifetimes) and are well matched to the typical ion plumes released from the IGISOL cooler-buncher. With limited, but critical, modification to the original design a trap suitable for use on the cooler-buncher platform was constructed and deployed at the IGISOL.

While successfully demonstrating the device was operational, initial tests showed that a physically larger trap with matched injection and extraction ion optics provides the desired spectroscopic performance. Such a trap has been developed on a bespoke testbed and will shortly be (re-)deployed at the IGISOL. The design, development, simulation and commissioning of the device along with future spectroscopic opportunities will be presented.

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### Measuring the nuclear masses of transuranium isotopes in the vicinity of the $N=152$ deformed neutron shell-closure

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We have re-visited the region of actinides in the vicinity of the  $N=152$  deformed neutron shell-closure, and repeated high-precision mass measurements using the newly implemented Phase Imaging Ion Cyclotron Resonance (PI-ICR) technique [1].

With our greatly improved apparatus we have measured the masses of  $^{244}\text{Pu}$ ,  $^{241}\text{Am}$ ,  $^{243}\text{Am}$ ,  $^{248}\text{Cm}$ ,  $^{249}\text{Cf}$ , taking  $^{208}\text{Pb}$  and  $^{238}\text{U}$  as mass references. The masses of these reference ions were recently determined with ultra-high-precision at PENTATRAP [2, 3]. We have implemented a simultaneous polynomial-fit method to evaluate the data.

Our results were implemented in the latest Atomic Mass Evaluation. The recent mass measurements as well as their comparison to the literature values will be presented and discussed.

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[3] Kromer, K., *et al.* Phys. Rev C **109.2** (2024): L021301.

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### Ion Trapping Developments using Printed Circuit Board Radio-Frequency Quadrupoles

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Radiofrequency quadrupoles (RFQ) are a widely used ion trapping device. They are used as cooler bunchers in mass and laser spectroscopy, or as stand-alone ion traps to provide insights into double beta decay modes and quantum research or in applications for chemistry and analytical sciences combined [1,2]. They feature high transport efficiencies and are able to produce narrow ion bunches, which makes them ideal injection traps for state of the art Multiple-Reflection Time-of-Flight Mass Spectrometers (MR-TOF-MS). Various research groups worldwide are partaking in the developments of injection traps for these MR-TOF-MS [3,4].

Common RFQ devices rely on round rods to create an almost ideal quadrupolar field. To guide ions along the structure the rods are typically segmented. These standard designs require precise alignment to ensure highest quality quadrupole fields and reduced field-boundary effect. Furthermore, for a smooth field, a large number of segments must be used [5,6]. This can make traditional RFQs difficult to manufacture.

In this contribution we will present a prototype for the new injection trap system for the MR-TOF-MS system at the FRS Ion Catcher, GSI. Based on a Printed Circuit Board RFQ [7], we have manufactured a simple 12 cm long prototype injection system. A new PCB RFQ has been commissioned using <sup>133</sup>Cs ions. It features a high efficiency and able to create bunch widths of <3ns using He buffer gas cooling.

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