LISA Conference
22-26 May 2023
Leuven, Belgium

This Marie Sklodowska-Curie Action (MSCA) Innovative Training Network (ITN) receives fundingfrom the European Union H2020 Framework Programme under grant agreement no. 861198

Contents

1 Invited Talks

1.1 Exploring frontiers of laser spectroscopy in current and future radioactive ion beam facilities

Speaker: Agota Koszorus
Affiliation: KU Leuven
Abstract: Our quest to understand the nuclear force is continuously driving developments on several frontiers. New experimental techniques are devised to gain access to short-lives isotopes and new observables, and at the same time tremendous effort is invested in developments aiming to improve the production yields of short-lived isotopes and deliver ion beams of elements which are currently not accessible. In this talk, a comprehensive overview of these aspects will be presented from the point of view of a laser spectroscopist. Recent experimental results will be used to introduce the state-of-the-art in laser spectroscopy and the new developments will be discussed in the context of emerging new facilities as well.

1.2 Probing Nuclear Structure with Laser Spectroscopy

Speaker: Bradley Cheal
Affiliation: University of Liverpool GB
Abstract: Laser spectroscopy provides model-independent measurements of nuclear ground and isomeric state properties. These include measurements of the nuclear spin, magnetic dipole and electric quadrupole moments and the mean-square charge radii. Such quantities provide a sensitive probe of single-particle effects and changing collective effects such as the nuclear size and shape. They provide a stringent benchmark of state-of-the-art calculations, such as those based on the shell model, ab initio calculations or density functional theory - with the last of these being applied to the actinides and achieving recent success across the nuclear chart. Optical spectroscopy complements nuclear decay spectroscopy methods in that it probes nuclear states directly, and these can be relatively long-lived. This is without reference to nuclear model assumptions. For example, spin assignments can be made unambiguously and these act as anchor points in the analysis of decay schemes. Unique access is provided to the mean-square charge radii of radioactive nuclei, which, unlike the quadrupole moment, is measurable for nuclei also with I<1. It is also sensitive to the quadrupole deformation in mean-square form (and thus can be used to infer nuclear rigidity) and higher order modes of deformation. In the actinide region, nuclear structure interests include the deformed shell gaps at Z=100 and N=152, the location and extent of the "island of stability", using the mean-square charge radius to infer nuclear octupole shapes or central depressions in the nuclear density, not to mention a wealth of isomeric states being available - including those which are particularly low-lying, fission isomers and K-isomers, for example. Representing the northern frontier of such studies, the atomic physics has to be developed at the same time. New transitions often need to be located, their suitability assessed for spectroscopic study and atomic parameters calibrated. Experimentally, while some research has used insource and/or collinear laser spectroscopy at ISOL facilities, in other cases a change of technique is required, adapting to a variety of production methods on a case-by-case basis.

1.3 Radiometals for Cancer Treatment at TRIUMF

Speaker: Cornelia Hoehr
Affiliation: TRIUMF
Abstract: Besides being Canada's particle accelerator centre with emphasis on nuclear, particle and accelerator physics, TRIUMF has a long history of medical isotope production and radiotherapy. Its unique infrastructure includes a number of cyclotrons with energies between 13 and 520 MeV and radiochemical facility to perform radiochemical separations and radiolabeling of medical isotopes. In recent years we have developed novel targetry and the production and separation of radiometals, including alpha and Auger emitters with promising potential for novel Targeted Radiation Therapy (TRT). These include the popular At-211 and Ac-225 but also more novel isotopes like Pd-103 or Hg-197.

1.4 Target microstructure engineering impact on the production of radioactive ion beams: the challenge of high boiling point elements

Speaker: Joao Pedro Ramos
Affiliation: Belgian Nuclear Research Center BE
Abstract: The Isotope Separation On-Line (ISOL) is a technique used to produce relatively-pure radioactive ion beams (RIBs) of several elements, with half-lives down to a few milliseconds. Lately, special attention has been given to the production of more refractory elements, for e.g. actinium (i.e. at ISOLDE/MEDICIS at CERN or at the future ISOL@MYRRHA in SCK CEN), or other heavier actinides (i.e. the LISA ITN Consortium). The material microstructure understanding and development for ISOL targets has been received special attention by the scientific community in the past 15 years. The development of more efficient materials which deliver high radioactive ion beam yields that are also constant over time, is now a priority for the ISOL facilities around the world. This is often a more time-efficient and cost-effective route when compared to e.g. increasing the beam power on target. The engineering of the target materials starts from the selection of the chemical compound(s) (e.g. oxide, carbide or metal materials), their shape (disk, foil, etc.) and microstructure (nano/microstructure which varies with grain size, porosity, etc.). The selected material, has to be compatible with the operation conditions of an ISOL system: stability in extreme radiation, at very high temperatures and in high-vacuum environments. There is often an optimum target material-release element pair, and sometimes even, a unique target material-isotope combination, where the half-life plays a crucial role on the isotope release efficiency from the target. Materials research has to be conducted to develop these very particular materials, rarely found in other applications and often materials used at different ISOL facilities are not interchangeable or need adaptations (e.g. low power/high energy facilities – i.e. ISOLDE vs. high power/low energy facilities – i.e. ISOL@MYRRHA). At the last steps, they have to be studied for the isotope release efficiency, either through release studies and/or target prototype tests. In some cases, and often in case of refractory RIB elements, the release can be assisted though the injection of a reactive gas which promotes the reaction of the element to be released with it, forming a volatile molecule which is easier to extract from the target. In this talk, an introduction to the importance of the ISOL target materials microstructure will be given, as well as an overview of the state of the art in ISOL target materials research. A list of dominant properties important/relevant for the release yield of refractory elements will be presented and which options can be used to optimize the related processes.

1.5 Radionuclide analysis with Accelerator Mass Spectrometry: Lasers make an ultra-sensitive technique more versatile

Speaker: Johannes Lachner
Affiliation: HZDR
Abstract: Accelerator Mass Spectrometry (AMS) is a powerful experimental technique to determine trace amounts of nuclides in environmental samples. This finds many applications, e.g. in archaeology, geology, nuclear astrophysics or oceanography. A successful AMS measurement combines efficient counting of the ions of interest with effective suppression of potential background arising from molecular and atomic isobars or from neighbouring abundant isotopes. At present, there are over 150 active AMS facilities worldwide, about 20% of which are capable or engaged in measuring actinides or fission products. In my presentation, I will explain how a series of technical developments has paved the way for the success of AMS measurements of long-lived actinides and fission products. The detection efficiency for heavy ions was improved by optimizing their transport through compact facilities, which in particular has made actinide AMS measurements attractive for studies of environmental samples with a number of examples in the geosciences or in nuclear astrophysics. Another step forward in the development of the AMS technique was the combination of a conventional AMS system with ion cooling, which provides suppression of isobaric background in a non-resonant interaction of the beam particles with a Laser. This has opened a new field for the measurement of 36Cl, 135Cs, 137Cs and other trace nuclides.

1.6 Atomic Properties of Heavy Actinides from Laser Spectroscopy

Speaker: Michael Block
Affiliation:
GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany;
Helmholtz-Institut Mainz, Mainz, Germany;
Johannes Gutenberg-Universität Mainz, Mainz, Germany
Abstract: The heaviest elements in the Periodic Table attract interest due to their peculiar atomic properties that differ from their lighter homologues [1]. Reasons for these deviations are so-called relativistic effects, quantum electrodynamics in a non-perturbative regime, and electron correlations. In the actinide series, the elements in the focus of the LISA network, these effects are accessible to experimental investigations by laser spectroscopy. Actinide elements with long-lived isotopes facilitate offline studies of reactor-bred samples. Such experiments have recently been carried out at the RISIKO separator of Mainz university, for example, and have provided a variety of new data for the elements from curium to fermium [2-4]. Measurements comprised the identification of several excited atomic states and the first ionization potential determined from the convergence of Rydberg series. The actinides beyond fermium are accessible at accelerator facilities as demonstrated in pioneering experiments on nobelium isotopes with the tailored RADRIS method at GSI Darmstadt, Germany [5,6]. In combination with atomic theory laser spectroscopic measurements also enable the investigation of nuclear properties such as the nuclear spin, electromagnetic nuclear moments, and changes in mean-square charge radii to study the nuclear shell-structure evolution in deformed nuclei around Z=100, N=152, for example. In this contribution I will give an overview of selected recent experimental atomic physics measurements in californium, einsteinium, fermium, and nobelium. Prospects for future measurements in other actinides will be addressed.
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of Nobelium, Phys. Rev. Letters 120, 263003.

1.7 Access to the nuclear properties with heavy muonic atoms

Speaker: Natalia Oreshkina
Affiliation: MPIK
Abstract: When coming close to an atom, a muon can be captured by the nucleus and form a hydrogen-like muonic ion, which is typically also surrounded by atomic electrons. This atomic system is commonly referred to as a muonic atom. Due to the muons high mass, it is located much closer to the nucleus; and, especially for heavy nuclei, this results in big nuclear size effects and a strong dependence of the muon bound-state energies on the nuclear charge and current distributions, as well as in large relativistic effects [1, 2]. A combination of the knowledge about the level structure and experiments measuring the transition energies in muonic atoms enabled the determination of nuclear parameters like charge radii, electric quadrupole and magnetic dipole moments [3]. Theoretical predictions of the fine-, hyperfine structure, and dynamical splitting of muonic atoms, based on rigorous QED calculations will be presented. State-of-the-art techniques from both nuclear and atomic physics are brought together in order to perform the most comprehensive to date calculations of the quantum-electrodynamics and nuclear contributions. Finally, a long-standing problem of fine-structure anomalies in muonic atoms is revisited in the light of the last improvements on nuclear-polarization [4] and self-energy calculations [5].
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1.8 Frequency control of continuous-wave laser sources

Speaker: Volker Sonnenschein
Affiliation: HÜBNER GmbH & Co. KG, Kassel, Germany
Abstract: Requirements on laser sources for high resolution spectroscopy of radioisotopes can be highly demanding. Atomic and molecular transitions of interest are widely spread over the electromagnetic spectrum from the deep UV to the far infrared, so that gain media with broad tuning range such as Ti:sapphire, dye lasers and optical parametric oscillators (OPO) are needed along with frequency converters. Alternatively, multiple lower priced systems, for example based on diode or quantum cascade laser technology, need to be installed for each targeted wavelength. Precise evaluation of nuclear moments or other properties is only possible if additional laser parameters, such as spectral linewidth, purity and mode-hop-free tuning range are suitable for the application. Classically, frequency selection and control in optical resonators is performed with combinations of spectrally dispersive elements, such as birefringent filters, gratings, prisms, etalons, and piezoelectric control of cavity dimensions. Such narrowband tunable laser sources are also of high interest in the generation of high intensity laser pulses with spectrally narrow features in injection seeded amplifiers, where systems based on cw-Dye, Ti:sapphire as well as OPO have been demonstrated for radioisotope measurements. A more compact solution could also be a self-seeded variant that combines cw-source and amplifier in a single cavity [1]. For highest stability, the laser can be locked to high Finesse optical cavities, either via optical feedback/self-injection [2] or electronic feedback. Promising developments here are the miniaturization of these cavities in the form of photonic circuits or whispering-gallery resonators.
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[2] Journal of Appl. Phys 2022, 132, 083102 https://doi.org/10.1063/5.0101732

2 Contributions

2.1 In vitro dosimetry for assessment of Targeted-Alpha-Therapy

Speaker: Alexis Doudard
Affiliation: Grand Accélérateur National d'Ions Lourds GANIL, CEA/DRF CNRS/IN2P3
Abstract: Targeted alpha therapy (TAT) is a potent internal radiotherapy of interest for the treatment of small and diffuse targets, such as brain metastases [1][2]. This therapy is based on alpha-emitting radionuclides with decay schemes convenient for clinical use, such as the actinides ²²⁵Ac and ²²⁷Th [3]. Developments of new TAT treatments include *in vitro* assays, where their biological effectiveness on tumor cells is compared to other reference treatments through imaging and dosimetry. However, while the short and dense ionization tracks in biological matter of alpha-emissions constitute the main interest of TAT, this property makes *in vitro* dosimetry heavily dependent on the spatial distribution of the radionuclides in the culture medium [4]. Measurement of this distribution is thus mandatory to back dose-effect relationship assessments and would improve reliability of comparisons with other treatment methods. We developed an *in vitro* dosimetry system, which can be used in a cell culture incubator, based on silicon semiconductor detectors recording energy spectra of the alpha-particles emitted within the culture wells and passing through the cell layer. A new spectral deconvolution method of the recorded energy spectra was developed and enables recovery of the spatial and time distributions of the radionuclides during the experiment. This method relies on a database made of pre-computed Geant4 simulations and is fast enough to allow on-line dosimetry of the assays. A validation applied to ²¹²Pb and ²²³Ra through simulation of *in vitro* irradiations demonstrated dose errors due to uncertainties on the computed spatial distribution being limited to 3%. The new experimental system and algorithm were employed in preliminary experiments with ²¹²Pb and ²²³Ra and showed that the spatial distribution of radionuclides is sensitive to the experimental conditions. They also revealed that the different radionuclides of complex decay chains, such as ²²³Ra, may present largely different spatial and temporal distributions, which has further consequences on the dose computation. All these results demonstrated the need for a radionuclide spatial distribution assessment to avoid significant dose misestimations and thus to improve the reliability of conclusions drawn from *in vitro* assays of TAT.
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Acknowledgements:
This project has received financial support from the CNRS through the MITI interdisciplinary program ISOTOP2020.

2.2 Comparison of theory and experiment for relative transition probabilities in thulium

Speaker: Andrey Bondarev
Affiliation: Helmholtz Institute Jena
Abstract: As actinides, lanthanides are characterized by dense and complex spectra due to the presence of an open f-electron shell. Theoretical treatment of such systems is usually faced with problems to provide accurate and reliable results for their properties. Here we report on comparing the results of ab initio calculations of electric-dipole transition intensities with the corresponding experimental data in atomic thulium. The calculations were done using a recently proposed modification of an approach that combines configuration interaction (CI) and many-body perturbation theory (MBPT) [M. G. Kozlov, I. I. Tupitsyn, A. I. Bondarev, and D. V. Mironova, Phys. Rev. A 105, 052805 (2022)]. The ground state configuration of thulium is [Xe]4f136s2, and it was considered as a 15 active-electron system with a frozen Xe-like core. Due to a large number of active electrons and plenty of Slater determinants in configurations with opened f-shell, the conventional CI approach can tackle only a configuration space (CS) with a moderate number of configurations. In our approach, the active orbitals are divided into valence and virtual. The CS is constructed by making single and double excitations from a few reference configurations to the valence orbitals and only single excitations to the virtual ones. The CS constructed in such a way still allows us to perform CI, while the contribution of the double excitations to the virtual orbitals is taken into account by calculating MBPT diagrams. The latter gives rise to additional terms added to the Hamiltonian in a form of effective radial integrals in the CI procedure. Once the many-electron wave functions of individual states are found, the intensities of electric dipole lines are calculated using the formalism of the transition matrix. In the experiment, relative line intensity distributions were obtained in Tm emission spectra ranging from 400 nm to 700 nm, applying a high-resolution Bruker IFS 125 HR Fourier-transform spectrometer at the Laser Centre of the University of Latvia. The 169Tm emission spectra were produced in a hollow cathode discharge lamp in the presence of either Ar or Ne buffer gases at different discharge current values. We found very good agreement between the measured and calculated relative intensity distributions in selected branches of Tm emission lines, which originate from a common upper state. In particular, 3 branches from upper state levels with energies 32217.195, 33943.282, and 35682.251 cm-1 were examined. The proposed theoretical approach can be extended for a prediction of electronic structure and properties of actinides that are the focus of the LISA consortium. The Riga team acknowledges support from the Latvian Council of Science, project No. lzp-2020/1-0088 “Advanced spectroscopic methods and tools for the study of evolved stars”

2.3 Towards in-gas-jet studies of isomeric 229Th+

Speaker: Arno Claessens
Affiliation:
Abstract: Short half-lives, low production rates and the need to produce them by fusion-evaporation reactions all complicate laser spectroscopy studies of (trans)actinides. The In-Gas Laser Ionization and Spectroscopy (IGLIS) technique has been succesfully employed in studies on short-lived actinides (see for instance [1,2]). The addition of a convergent-divergent (de Laval) nozzle to create a cold hypersonic gas jet combines efficiency with sub-GHz spectral resolution. The new generation of nozzles with a Mach number of 8 enables laser spectroscopy studies of actinides with spectral resolutions around 200 MHz [3]. The light actinide ^{229}Th and its nuclear clock isomer have attracted significant attention in the last years. A remarkable feature is the suggested short half-life (< 10 ms) of the isomer in its, not-yet observed, singly charged state [4]. We report on the design of a fast-extraction gas cell (evacuation time of ~ 1 ms) and tailor-made recoil ion sources of ^{233}U prepared by TU Vienna and JGU Mainz which are installed inside the gas cell to provide the isomeric thorium ions. A new set of de Laval nozzles was designed and characterized to operate under the required low-stagnation-pressure conditions of the recoil sources as well as for spectroscopy studies of (trans)actinides in the JetRIS experiment at GSI [5].
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2.4 The PI-LIST: High-resolution crossed-beams laser spectroscopy inside the ISOLDE laser ion source.

Speaker: Asar A H Jaradat
Affiliation: CERN

Abstract: Laser resonance ionization spectroscopy in the ion source coupled directly to the isotope production target has been 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 below the GHz regime. 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, an order of magnitude below usual limitations. It is based on the high beam purity Laser Ion Source and Trap (LIST) [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. Laser-atom interactions take place in an RFQ structure directly downstream, where solely element-selective laser ionization takes place. In the so-called Perpendicularly Illuminated LIST (PI-LIST) [4] a crossed laser/atom beam geometry is used for spectroscopy, therefore only the transverse velocity spread of the effusing atom ensemble contributes to the experimentally observed Doppler broadening. Following the integration of this device as the standard tool for high-resolution spectroscopy applications at the off-line mass separator facility at Mainz University [5, 6], we present its first on-line application at ISOLDE for nuclear structure investigations. Neutron-rich actinium isotopes in the region of assumed octupole deformation [7] were studied with the highest spectral resolution ever achieved for in-source resonance ionization spectroscopy at ISOLDE. 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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2.5 SATLAS 2: The updated package for analysis of counting data

Speaker: Bram Van Den Borne
Affiliation: KU Leuven BE
Abstract: SATLAS is a Python package for the analysis of hyperfine structure spectra from laser spectroscopy. The first version of the package was released in 2018 [1] and was quickly adopted by the community, cited in numerous high impact papers [2,3]. SATLAS 2 (https://iks-nm.github.io/satlas2/), released in 2023, is a new version of SATLAS, built with a simpler structure and offers speed-up of a factor 20-300 for fast simultaneous fitting of multiple spectra. It includes the simple chisquare fitting, maximum likelihood fitting and error estimation by performing random walks, as in SATLAS 1. The error estimation by random walk is extended to allow linear combinations of different walker moves for a better sampling of the random walk in parameter space. Furthermore, SATLAS 2 now offers easy implementation of custom models, such that non-laser spectroscopy data can also be analyzed with SATLAS. In this contribution I will present the changes between SATLAS 1 and SATLAS 2, showing its speed-up with examples. Further, I will explain the different statistical methods that are implemented and how it can be used in Python.
References:
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2.6 Collinear resonant ionization spectroscopy of RaF

Speaker: Carlos Mario Fajardo Zambrano
Affiliation: KU Leuven BE
Abstract: With the advancement of spectroscopic techniques at radioactive beam facilities, the spectroscopy of radioactive molecules has been achieved in the past few years at ISOLDE (CERN) using the Collinear Resonance Ionization Spectroscopy (CRIS) experiment [1]. Radioactive molecules are a promising discovery tool for diverse fields [2]. Among them, diatomic polar molecules are at the center of theoretical and experimental investigations in search of the electron's electric dipole moment (eEDM) and nuclear Schiff moments [3-5]. Due to the strong electric field and the rich electronic, vibrational, and rotational structure inherent in molecules, the sensitivity to Schiff moments is expected to be enhanced in radioactive polar molecules, such as RaF [6]. However, their molecular structure is poorly known, requiring preparatory spectroscopic studies of the electronic structure of the molecule. After two experimental campaigns at CRIS (2018, 2021), many electronic levels in RaF have been studied with broadband laser spectroscopy, as well as one optical transition in high resolution [7]. This has shown the capacity of collinear laser spectroscopy at radioactive ion beam facilities for the study of radioactive molecules, as well as benchmarking the predictive power of state-of-the-art quantum chemistry. Focusing on RaF as a case-study, this talk will present the study of eEDM on molecules, along with the basic principles of molecular spectroscopy. An overview of the CRIS technique and the features associated with the spectroscopy of radioactive molecules will also be presented.
References:
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scheme of a radium-containing molecule, In preparation (2023).

2.7 Status of development of the JetRIS project for laser spectroscopy of the heavy actinides at GSI/HIM

Speaker: Danny Münzberg
Affiliation: GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, DE; Helmholtz-Institut, Mainz, DE; Johannes Gutenberg-Universität, Department Chemie, Mainz, DE

Abstract: Laser spectroscopy is used at the Separator for Heavy Ion Products (SHIP), located at GSI-Darmstadt, Germany, to study atomic and nuclear properties in the heavy actinide region. Due to low production rates for nuclides in this region, typically less than one ion per second, highly efficient and highly sensitive spectroscopy techniques are required. The Radiation Detected Resonance Ionization Spectroscopy (RADRIS) technique [1] successfully used in previous measurements for nobelium [2,3] faces limitations on the spectral resolution and is not very well suited for studies of short-lived species. Therefore in a new approach the in-gas-jet resonant ionization (JetRIS) apparatus [4] has been built to perform high-resolution laser spectroscopy of heavy actinides. Commissioning measurements using laser-induced fluorescence of ^{164}Dy [5] were performed to characterize the spectral resolution of the system. The overall efficiency and transport time of ions in the JetRIS setup were investigated using a ^{223}Ra recoil ion source emitting ^{219}Rn and its progenies. Recently, the $^1S_0 \rightarrow {}^1P_1$ atomic transition in ^{254}No was measured with JetRIS, resulting in an almost order of magnitude improvement in the spectral resolution compared to the RADRIS measurements reported in [3]. Furthermore, a multi-reflection time-of-flight mass seperator (MR-ToF MS) will be build and integrated into the JetRIS setup to allow for different methods of detection enabling studies on a wider range of isotopes. An overview of the latest beamtime results and the characterization measurements will be given. Developments of the system as well as prospects for future measurements will be discussed.

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2.8 Multi-element ultra-trace analysis of hot particles in the Chornobyl Exclusion Zone

Speaker: Darcy Van Eerten
Affiliation: IRS-LUH
Abstract: Nuclear materials that contaminate the environment present an ongoing challenge to characterize due to their small size and diverse morphology. The analysis of isotope ratios in actinides and fission products can provide determination of origin, age and environmental weathering of these materials. Resonance ionisation mass spectrometry (RIMS) utilizes selective laser ionization to target single elements and suppress the isobaric interferences typically found in mass spectrometry. Two specialized instruments were used to analyse single hot particles from Chornobyl: rL-SNMS at the IRS in Hannover, Germany, and LION at LLNL in Livermore, USA. Results from multiple particles are presented with interpretations of isotope ratios in U, Pu, Cs, Rb, Sr and Ba.

2.9 Numerical simulation of heavy ion stopping and transport in the JetRIS gas cell at GSI

Speaker: Fedor Ivandikov
Affiliation: KU Leuven BE
Abstract: Laser spectroscopy research into heavy actinides has been garnering interest in recent years, as laser spectroscopy techniques advance and become applicable in studies of heavier species. These studies are, however, complicated by low cross sections involved in the production of these isotopes and their short half-lives. The IGLIS technique has been a mainstay in laser spectroscopy studies of the heavier elements. In particular JetRIS is designed for high-efficiency high-resolution resonant ionization spectroscopy with target to detector transport times in the range of hundreds of milliseconds. The working principles of the technique are to stop the fusion evaporation products in a gas cell, transport the thermalized species via electrostatic potentials and gas flow to a tantalum filament, where they are desorbed as neutrals and carried into the low pressure and low temperature hypersonic gas jet, where the atoms are laser ionized. In the 2022 beamtime at GSI the JetRIS experiment was commissioned and produced its first results. The experiment was successful in producing spectra of nobelium with a seven-fold improved resolution compared to convention gas cell experiments, thus establishing the viability of the technique. Analysis of the acquired data showed that the experiment is currently being held back by low gas cell extraction efficiency (on the order of 0.1%). This calls for detailed simulation studies of the gas cell to try to understand the system and improve its performance The current work presents an extensive model created in the COMSOL simulation environment, the benchmarks of this model against experimental data and simulations of the impact potential modification will have on the systems performance.

2.10 Resonance laser ionization and mass separation of 225Ac: Challenges, capabilities and perspectives

Speaker: Jake David Johnson
Affiliation: KU Leuven BE
Abstract: The medical radioisotope 225Ac is an actinide that can be produced by high energy proton spallation of thick thorium- or uranium-based targets. The method of offline resonance laser ionization and mass separation (RIMS) can then be applied in order to extract 225Ac with high purity. Since 2020, four collections of 225Ac have been performed at CERN MEDICIS, producing several samples, most of which have been sent to KU Leuven for thorough characterization using a combination of spectroscopy methods. Gamma-gamma coincidence spectroscopy and low-background gamma spectroscopy provide absolute activity measurements, while the sensitive techniques of alpha-decay and alpha-recoil spectroscopy are used to measure the activity of long-lived alpha-emitting trace impurities such as 227Ac. In this contribution, the challenges of extracting 225Ac with high efficiency using the RIMS technique will be discussed, based on experiences from the multiple collections over the past three years. Special emphasis will be put on the systematics of the ionization efficiency of the resonance ionization laser ion source. Furthermore, the decay spectroscopy techniques used to determine the isotopic composition of the resulting samples will be discussed. The technique of alpha-recoil spectroscopy that has allowed the determination of trace activities of 227Ac in the samples, through probing only the alpha-decay daughter chains of the implanted isotopes will be discussed in detail. Finally, the results will be summarized to bring perspective to how the combination of high energy spallation of uranium or thorium followed by RIMS could contribute to the global 225Ac supply.

2.11 Into the unknown: studying the heaviest actinides by laser spectroscopy

Speaker: Jessica Warbinek
Affiliation: GSI Darmstadt, Johannes Gutenberg-Universität Mainz. Germany
Abstract: Experimental studies tailored to unveil fundamental properties of the heaviest actinide elements have recently gained increasing interest and yet the available information remains sparse. Nuclides in this region of the nuclear chart are stabilized by shell effects that retard spontaneous fission and they feature properties distinctly different from those of lighter nuclides. In addition, the atomic structure of these heavy elements features an enhanced impact of relativistic effects affecting their chemical properties compared to the lighter homologes [1]. Laser spectroscopy is a powerful tool to investigate atomic structures of these heavy elements. With information on atomic levels and their hyperfine structures, experimental information on nuclear parameters such as the change in the mean-square charge radii and nuclear moments becomes accessible in a nuclear-model independent manner [2]. However, predictions of such atomic and nuclear properties by state-of-the-art theoretical models are challenging and experimental studies are hampered by limited production capabilities and short half-lives of these nuclides. First experimental observations of this kind were pioneered by the dedicated RAdiation Detected Resonance Ionization Spectroscopy (RADRIS) method in the heavy actinide element nobelium ($Z = 102$) produced in atom-at-a-time quantities at the SHIP separator at GSI [3,4]. Recent advancements of the setup and a novel production scheme via accumulation of decay daughters from recoil nuclei produced directly in fusion-evaporation reactions gave access to nuclides which were previously not in reach. This enabled first on-line laser spectroscopy studies of fermium ($Z = 100$) down to minute production rates. On-line and off-line laser spectroscopy techniques were combined and significantly advanced to measure isotope shifts and extract changes in the nuclear mean-square charge radii for a chain of eight isotopes ranging from the accelerator-produced ^{245}Fm to the reactor-bred ^{257}Fm across the known deformed shell gap at $N = 152$. Tackling studies in even heavier elements, such as the search for atomic levels in the heaviest actinide, lawrencium ($Z = 103$), with a tenfold lower production rate as in the nobelium isotone, the increased sensitivity of this setup [5] will give a decisive benefit. Recent results and methodological advancements achieved within the LISA framework will be discussed in view of further perspectives for laser spectroscopy of the heaviest elements. The presented experimental observations give insight into the nuclear structure of the heavy actinides supporting new developments in theoretical models which will eventually improve their predictive power towards the heaviest elements.
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2.12 Charge radii measurements of $^{26-34}$Al transitioning into the $N = 20$ island of inversion

Speaker: Jordan Ray Reilly
Affiliation: University of Manchester GB
Abstract: The isotopic chain of neutron-rich Al provides an ideal probe to investigate the evolution of nuclear structure within the vicinity of the $N = 20$ island of inversion. With $Z = 13$, Al is located between spherical Si[1] ($Z = 14$) and deformed Mg[2] ($Z = 12$). As ^{32}Mg is the centre of the $N = 20$ island of inversion, the neighbouring Al isotopes provide an excellent opportunity to investigate the transition into the island of inversion. Currently, charge radii measurements of radioactive isotopes in this region are limited up to the $N = 20$ shell closure for Mg[2] and Na[3], and $N = 19$ for Al[4]. The CRIS collaboration recently measured $^{26-34}$Al using laser spectroscopy, crossing the $N = 20$ shell closure, building on previous results measured at ISOLDE, CERN[4]. In this talk, a brief overview of the CRIS technique will be presented along with recent measurements of the changes in the mean-squared charge radii of ^{33,34}Al, crossing $N = 20$ for the first time in this region. These results will be discussed in relation to the $N = 20$ island of inversion and compared with neighbouring isotopic chains.
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2.13 New Experimental Prospects for the MARA-LEB Facility

Speaker: Jorge Romero
Affiliation: University of Liverpool
Abstract: The Low-Energy Branch (LEB) [1] for the MARA separator [2] is a facility under construction at the Accelerator Laboratory of the University of Jyväskylä. The facility will be used to study the ground-state properties and decay modes of exotic nuclei far from stability combining multiple techniques to investigate nuclear properties of isotopes far from stability. MARA-LEB will stop and neutralise reaction products selected by the MARA separator in a small-volume buffer gas cell. A state-of-the-art Titanium:Sapphire laser system allows for re-ionsiation of selected species and for laser spectroscopic analysis. Re-ionised atoms can be extracted and accelerated by the ion transport system [3] and further mass- and velocity-selected before being directed either into specialised detector stations, for decay spectroscopy, or a dedicated cooler-buncher and Multi-Reflection Time-of-Flight Mass Spectrometer, for high-precision mass measurements. In a recent experiment at MARA, where the dynamics of non-fusion reaction channels was studied by the GSI-JYFL collaboration various heavy nuclei in the $84 \leq Z \leq 92$ region, which includes some light actinides, were produced. Data analysis from this experiment is still under way [4]. Nevertheless, preliminary experimental yields show that laser spectroscopy of these heavy nuclei may be feasible in the MARA-LEB facility. This is a promising prospect given the recent increased interest in the study of exotic species in this region via the use of laser spectroscopical techniques [5]. There is limited information on the actinides due to low production cross-sections combined with the lack of stable isotopes for many of the elements in this group. The use of non-fusion reactions such as Multi-Nucleon Transfer (MNT) has been proposed as a way to enhance access to this region of the nuclear chart and thus improve the prospects for laser ionisation of these elements. MARA-LEB will combine the required mass resolution and laser spectroscopic capabilities to carry out studies in with these new experimental conditions. An update on the current status of MARA-LEB will be presented, alongside a discussion of the feasibility of laser spectroscopy experiments in the new facility given the cross-sections extracted from these recent MARA experiments.
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2.14 Ab initio Multi-configurational Dirac-Hartree-Fock (MCDHF) calculations of the energy spectrum of neutral Lawrencium

Speaker: Joseph S. Andrews
Affiliation: Friedrich Schiller University Jena
Abstract: The study of the actinides lies at the frontier of contemporary nuclear and atomic physics research. Lawrencium, with 103 protons, is the heaviest and final actinide in the periodic table, however few experimental results exist for neutral Lawrencium. Calculations of the energy spectrum were initially performed on its lighter homologue Lutetium for which experimental results exist. Lutetium is calculated in order to determine the predictive accuracy of the calculations and suitability of the model in calculating the energy spectrum and transition properties of Lawrencium. The energy spectra of Lawrencium and Lutetium are investigated using Multi-configurational Dirac-Hartree-Fock (MCDHF) method and the preliminary results of the latter are presented. In addition, a multireference (MR) set is built containing configuration state functions (CSFs) which significantly contribute to the reference level wavefunction. The calculations are performed using a layer-by-layer approach. The spectroscopic orbitals in the multireference are generated in Dirac-Hartree-Fock mode without correlation. Higher layers are generated by allowing excitations from the multireference into the virtual layers.

2.15 Spectral investigations of pulsed narrow-linewidth Ti:sapphire lasers and laser spectroscopy of stable Dy in preparation of high-resolution in-source laser spectroscopy of lanthanides

Speaker: Julius Wilhelm Wessolek
Affiliation: University of Manchester GB
Abstract: Pulsed amplification of narrow-band continuous-wave laser light with injection-seeded Ti:sapphire lasers has become a widespread and useful tool for high-resolution resonance ionization spectroscopy at Radioactive Ion Beam (RIB) facilities. The output characteristics of several lasers of this type and their dependency on the seed parameters have been investigated both experimentally and theoretically and will be presented. Understanding this behaviour is an important factor guiding future developments to further improve their spectral performance. The combination of the Perpendicularly Illuminated Laser Ion Source and Trap (PI-LIST) with an injection-seeded Ti:sapphire laser enables in-source laser ionization spectroscopy with high resolution and increased background suppression, which has had its first successful application at CERN ISOLDE on Ac in 2022. Following the Letter of Intent 246 on yield measurements of the lanthanides with a LIST at ISOLDE, high-resolution laser spectroscopy of stable dysprosium (Dy, Z=66) has been conducted and will be presented together with Dy yield measurements in preparation of future plans of revisiting Dy for high-resolution in-source laser spectroscopy.

2.16 Development of a time-of-flight mass spectrometer with a laser desorption / ionization source

Speaker: Keerthana Kamalakannan
Affiliation: GIP ARRONAX and Laboratoire SUBATECH
Abstract: SMILES (Séparation en Masse couplée à l'Ionisation Laser pour des applications Environnementales et en Santé) mass separator is being developed in SUBATECH laboratory to analyse isotopes not only for environmental application but also for medical purpose. Two types of mass separators will be built: one using a dipole magnet combined with a hot cavity ion source and the other, a time-of-flight mass spectrometer (TOF-MS) with a laser desorption-ionization (LDI) ion source. In both cases, laser/resonant ionization will be employed to selectively and efficiently promote the atoms into their excited and ionized states by photoionization. In this current study, we first focus on the development of a TOF-MS, one of its use will be to analyse the contaminants present in environmental samples. To design this TOF-MS, SIMION software has proven useful in studying the ion trajectories in electric and magnetic fields [1, 2]. **About the work** A TOF-MS differentiates the mass of different elements based on their time-of-flight inside the analyser before reaching the detector. This TOF is proportional to its $\sqrt{m/q}$ ratio. A TOF-reflectron MS (TOF-RMS) will be developed for the SMILES project for which a TOF-linear MS (TOF-LMS) will be a pilot prototype that will guide us in studying the LDI ion source in addition to understanding various components involved in it. Using the SIMION software, a 2-step voltage extraction zone proved to have better mass resolution and spatial distribution on the detector. Simulation studies are carried out for various elements like Cu, Er, Ra, U and Pu as they are either long-lived or stable contaminants in the environment. Ions of these elements with initial kinetic energy = 0.65 ± 0.065 eV are studied, considering their energy spread and velocity direction distribution. **Conclusion** The current prototype of TOF-LMS can separate a mass upto 280 considering a 10% valley resolution (Rv10=m2/Δm). An einzel lens after the acceleration zone improves the TOF resolution and avoids ion loss out of detector. As the simulated and the modelled values are in agreement with each other with a small deviation, the TOF-LMS will soon be commissioned.
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2.17 Laser Spectroscopy of Short-Lived Radioactive Atoms

Speaker: Kieran Flanagan
Affiliation: University of Manchester GB
Abstract: Laser Spectroscopy of Short-lived Radioactive Atoms Duggan M.1, Flanagan K.1, Edwards G.1, Woodbury S.2 1University of Manchester, Manchester, United Kingdom 2National Nuclear Laboratory, Central Laboratory, Sellafield, United Kingdom The reported total volume of nuclear waste in the UK inventory is 4.56 10^6 m3 with 94% of the volume classified as low-level waste, LLW, and very low-level waste, VLLW. However, the inventory of LLW-VLLW cross-boundary waste at 1.56x105 m3 would benefit from an estimated saving of more that £1000 per m3 in disposal processes if the characterisation of radionuclides were correctly identified. Detecting the abundance of 90Sr in the soil, groundwater and building materials near nuclear power plants serves to (i) reduce the cost of disposal due to correct identification of cross-boundary waste, and (ii) provide an accurate means of monitoring the abundance of carcinogenic radioisotopes in the environment. Both are significant for the safe operation, maintenance, and decommission of a nuclear reactor site. The aim of the over-arching project, which this PhD project is a sub-component of, is to develop a rapid and cost-effective method for the detection of radionuclides from environmental samples. This is to be achieved by hyphenating the Collinear Resonance Ionisation Spectroscopy (CRIS) with Inductively Coupled Plasma Mass Spectroscopy (ICP-MS). The primary aims of the PhD project is to develop the ion manipulation instrumentation for combining the techniques, quantify the current limits of detection of 90Sr, develop a laser scheme for 90Sr, and constructing the ICP-MS-CRIS instrument. A linear Paul trap, consisting of four PCBs, has been developed to cool and bunch a continuous ion beam. By superimposing an alternating RF potential onto a DC potential gradient and utilising a buffer gas, ions entering the trap are confined along the central axis by the RF potential while simultaneously being constrained in the same axis at given point due to the DC gradient. The design, simulation, manufacture, and construction of the trap has been conducted. The trap is currently being characterised and prepared for deployment in a CRIS instrument at the University of Manchester, the hyphenated ICP-MS-CRIS instrument, and the CRIS instrument in ISOLDE, CERN. Manual ion trapping has been achieved thus demonstrating the feasibility of the technology. Injection and extraction electrodes, placed either side of the trap, have been introducing the accelerate and decelerate the ion beam to suit its application. Further development will see the introduction of a floating potential to allow the trap to receive and transmit ion beams over a range of energies. Additionally, an ion extraction unit has been designed and manufactured to remove ions from the ICP-MS instrument before introducing the beam into the trap. Development of this unit is occurring in parallel

to the trap. A test rig and Faraday cage have been assembled to develop the ion manipulation instrumentation. The ability to design and construct custom instrumentation via the PCB format reduces production costs along with standardising current and future CRIS experiments for applied and fundamental research.

2.18 Preparation and characterization of Pu-239 and Pu-240 recoil ion sources for U-235m studies.

Speaker: Lauren Reed
Affiliation: JGU
Abstract: Alpha-decaying radioisotopes can be used as sources for their daughters, which can emerge from thin films containing the mother isotope. Such recoil sources provide free atoms or ions of hard-to-obtain nuclides. One example is U-235m, with a half-life of 26 min [1]. It decays by conversion electron emission to the U-235 ground state. The U-235m is the second-lowest lying known isomeric state (after the 8.1 eV Th-229m isomeric state), located at 76.7 eV excitation energy [2-4]. It is available as the alpha-decay daughter of Pu-239, which populates the isomer with a branching of 99.8% [1]. U-235m and its hyperfine structure are the focus of collinear laser spectroscopy (CLS) at Univ. Jyväskylä, Finland. To enable these studies, nineteen Pu-239 recoil ion sources with activities in the range of 60 – 190 kBq were prepared by the molecular plating (MP) technique [5-6] at Univ. Mainz, Germany. The interest in these ultra-low-lying isomers, which bridge nuclear and atomic physics and are of interest in the particle physics community, arises from the inclination to, e.g., develop nuclear clocks with the potential to outperform current atomic clocks by employing nuclear transitions rather than transitions in the electron shell [3]. To provide U-236, which has no hyperfine structure, Pu-240 recoil ion sources were prepared. This will be used as a reference ion for yield studies and CLS. In MP, the isotope of interest is dissolved in an organic solvent and is then electrodeposited onto a conductive cathode backing, creating a uniform thin layer [5-6]. MP is an attractive method for producing recoil ion sources providing a high rate of daughter isotopes [7]. High deposition yields of $\geq$ 90 % can be achieved in a single deposition step, it is a reliable technique, and the deposited layer generally is well bonded onto the backing. Since its development in the 1960s by Parker and Falk, the method has been optimized, e.g., in Mainz by Vascon et al., who investigated substrate roughness, plating solvent, applied current density, and electrolyte concentration to produce smooth,crack-free sources [6, 8-9]. The rate at which the daughter nuclides become available for CLS studies is a key performance indicator of the produced recoil ion sources. During MP, parameters such as total activity plated, source homogeneity, substrate roughness, and plating solvent can significantly influence the recoil efficiency and hence the daughter nuclide emission rate. Therefore, the plating method must be optimized to establish the best parameters for more efficient recoil ion sources. At the LISA 2023 conference, the production and characterization of Pu-239 and Pu-240 recoil ion sources by MP from N,N-Dimethylformamide (DMF) will be discussed. Various sources differing in dimension, activity, substrate, and drying procedure have been prepared, giving rise to Pu-239 and Pu-240 recoil ion sources

with a striking variety of colors. Sources have been characterized using radiographic imaging, alpha- and gamma spectroscopy, scanning electron microscopy (SEM), and Rutherford backscattering spectrometry (RBS). The latter renders Pu the heaviest element to date to have been measured by RBS at Univ. Jyväskylä. Finally, the current status and plans of Pu-239 recoil ion source production and characterization will be discussed at the conference, including the first preliminary results from the new Detection of Internal Conversion Electrons (DICE) apparatus established at Univ. Mainz for the experimental determination of U-235m recoil efficiencies via the detection of the emitted conversion electrons.

This project has received funding from the European's Union Horizon 2020 Research and Innovation Programme under grant agreement number 861198 project 'LISA' (Laser Ionization and Spectroscopy of Actinides) Marie Sklodowska-Curie Innovative Training Network (ITN).

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2.19 The NEXT setup to study neutron-rich transfermium nuclei

Speaker: M. Brajkovic
Affiliation: University of Groningen, the Netherlands
Abstract: Multinucleon transfer reactions can provide access to the heaviest, neutron-rich, actinide elements with relatively high cross-sections. The main drawback of this technique is the wide angular distribution of the multinucleon transfer products which makes it experimentally challenging to prepare precision measurements of transfer products. To overcome these limitations, the NEXT experiment [1] is being prepared at the PARTREC facility in Groningen. The production target is placed inside superconducting 3-T solenoid magnet and irradiated by high intense heavy ion beams delivered by the AGOR cyclotron. Target-like products are separated and focused with the magnet toward a gas catcher where they are slowed down. A newly developed ion guide [2] is used to capture, bunch and transfer the ions to MultiReflection Time-of-Flight Mass Spectrometer (MR-ToF MS) [3] for isobaric separation and precision mass measurements. In the contribution, we will present an overview of the NEXT setup, its current status and the planned experimental program.
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2.20 Hyperfine structure and isotope shift in the atomic spectrum of neptunium

Speaker: Magdalena Anna Kaja
Affiliation:
Abstract: Neptunium, with atomic number 93, is a radioactive actinide and the first transuranic element. In particular, the isotope ^{237}Np is generated quantitatively within the nuclear fuel cycle with typical amounts of ∼10 kg in each conventional pressurized water reactor per year [1]. Due to its long half-live of $2.1{\cdot}10^6$ years and high radiotoxicity in the up to 12 subsequent decays along the neptunium series, it represents a major hazard in the final disposal of nuclear waste. Under environmental conditions, Np can be present in four different oxidation states +III to +VI, and can form soluble species. In this context ultra-trace analysis of Np in environmental samples is of high relevance [2]. The development of efficient and selective non-radiometric determination methods using laser mass spectrometry relies on the identification of ionization schemes and detailed atomic spectroscopy [3]. For example, for quantitative isotope ratio determination by resonance ionization mass spectroscopy (RIMS), it is important to take into account the isotope-related effects stemming from hyperfine structures (HFS) and isotope shift (IS). For this purpose, new two-step excitation schemes were investigated for their suitability for neptunium analytics. Narrow bandwidth spectroscopy on ^{237}Np and ^{239}Np was carried out at the high transmission mass separator RISIKO using the PI-LIST laser ion source geometry [4]. Optical transitions were studied using a cw Ti:sapphire laser system [5] for seeding and injection locking of a pulsed Ti:sapphire amplifier [6]. The injection-seeded Ti:sapphire laser has a spectral bandwidth of 20 MHz, providing pulsed operation at a repetition rate of 10 kHz and high-power density as required with 150 mW average power after frequency doubling. The HFS of the atomic ground-state transitions to the levels at 25 075.15 cm^{-1} (J = 13/2) and at 25 277.63 cm^{-1} (J = 9/2) have been measured and hyperfine coupling constants for both isotopes as well as the isotope shifts between ^{237}Np and ^{239}Np have been determined. Additionally, the HFS of the atomic transition between the atomic ground state, as well as the thermally excited state at 2 033.94 cm^{-1} and the level at 25 342.55 cm^{-1} (J=11/2), has been measured for ^{237}Np. Experiment and data are discussed in the framework of the analysis of the atomic structure of the lighter actinide elements.
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2.21 Non-destructive resonance ionization mass spectrometry of spent nuclear fuel particles

Speaker: Manuel Raiwa
Affiliation: LLNL
Abstract: The profound characterization of spent nuclear fuel is of great importance in several research areas. Especially knowledge of elemental and isotopic composition are the base for further conclusions in the fields of nuclear forensics, safeguards and risk assessments. Classical approaches with mass spectrometry usually involve extensive chemical preparation to separate isobaric interference. Decay-counting based methods on the other hand are limited by atomic inventory and half-life of the radioactive isotopes. In some cases the sample is limited to particles of a few µm in diameter. This makes individual measurements with traditional methods unfeasible. One example of such so-called *hot particles* are fragments of the destroyed reactor core in the vicinity of the Chernobyl power plant. Static resonant laser secondary neutral mass spectrometry (rL-SNMS) is the only technique capable of measuring these particles individually with resolved isobaric pairs like Pu-238/U-238 and Am-241/Pu-241. It combines all the advantages of a commercial Tof-SIMS with the high selectivity of resonance ionization. The pulsed primary ion beam consumes only negligible amounts of sample material and the method does not need destructive chemical preparation. Recent developments in the field of two-photon excitation schemes enabled the detection of trace elements like curium at concentrations below 1 g/t in an individual particle. Taking its small size into account, this corresponds to only 10^7 atoms in the whole sample. While the method has great potential in the future, currently there are no commercial systems available. Only a hand full of self-built instruments is in operation world wide. This includes the LION facility at the Lawrence Livermore National Laboratory (LLNL) in the USA and the rL-SNMS System at the Institute of Radioecology and Radiation Protection in Hannover Germany. Here we will present the study of ten micrometer sized particles from the Chernobyl Exclusion Zone performed in Hannover. Isotopic ratios of several relevant actinides have been measured and can be compared to bulk measurements of RBMK-1000 spent nuclear fuel. The results show that the system can determine a possible source term based on the isotope ratios. Lastly an outlook is given on possible future developments to determine elemental ratios at the LION facility at LLNL.
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

2.22 Hyperfine structure calculations of excited states of lawrencium using the relativistic Fock-space coupled cluster method

Speaker: Martijn Reitsma
Affiliation: University of Groningen
Abstract: Atomic structure calculations in combination with spectroscopy are very effective for determining nuclear properties independent of nuclear models. Nuclear dipole and quadrupole moments can be extracted from calculations of the electrons' magnetic field and electric field gradient combined with hyperfine structure measurements[1,2]. We use the high-accuracy relativistic Fock-space coupled cluster method[3] with the finite field approach[4] to determine these hyperfine structure parameters for the lawrencium atom, which will help planned experiments to target the states that are most sensitive to the nuclear moments. Basis set, electron correlation and relativistic effects are investigated to assign uncertainties on the calculated values. This is essential for combining our results with experimental data.
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2.23 Production of actinide atomic and molecular ion beams at CERN-ISOLDE

Speaker: Mia Au
Affiliation: CERN
Abstract: The ISOLDE facility at CERN provides ion beams of nuclides across the nuclear chart produced in reactions between 1.4-GeV protons and thick targets. The development of molecular ion beams is motivated by improvements to beam extraction and purity as well as by interest in studying the radioactive molecules themselves. Molecules have been studied as a method to efficiently deliver beams of release-limited refractory elements by forming and extracting volatile molecules [1,2] of, e.g., carbon [3], boron [4], or refractory metals [5]. Molecular sideband extraction is also used as a technique to improve beam purity by shifting the species of interest away from background-dominated isobars into cleaner regions. Molecular beams additionally provide opportunities for fundamental physics studies at radioactive beam facilities [6-11]. We present results of actinide molecular ion beam development at ISOLDE using uranium carbide targets with injection of reactive tetrafluoromethane (CF_4) gas. The ion beam composition was studied using: the ISOLTRAP Multi-Reflection Time-of-Flight Mass Spectrometer (MR-ToF MS) [12] for identification by ToF mass measurements, online γ-ray spectroscopy at the ISOLDE tape station [13,14], and off-line α- and γ-ray spectrometry of ion-implanted samples. Atomic and molecular actinide ion beams have been produced and are reported. The results contribute to the development of actinide beams and to radioactive molecule production for fundamental physics research.
This project has received funding from the European Union's Horizon 2020 Research and Innovation Program (grant number 861198 project 'LISA' MSC ITN) and support by the German Federal Ministry of Education and Research (BMBF) (grant numbers 05P18HGCIA, 05P21RDFNB, and 13E18CHA, Wolfgang Gentner Program)
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2.24 Studying radioactive negative ion production cross sections

Speaker: Miranda Nichols
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Abstract: The valence electron of a negative ion is not bound by a long-range Coulomb potential but instead a shallow induced dipole potential which mainly arises from electron-electron correlation. As a result, negative ions have binding energies of about an order of magnitude smaller than neutral atoms. These correlation effects can be probed by measuring the electron affinity (EA) which is the amount of energy released when an electron binds to a neutral system to form a negative ion. Little is known about the structure of radioactive negative ions. Such studies are of interest for benchmarking atomic theory as well as medical and environmental applications e.g., targeted alpha therapy and uranium mine management. The first EA investigations for radioisotopes were of iodine-128 (128I) [1] and astatine (At) [2] made at CERN-ISOLDE. However, the production of radioactive negative ion beams can be significantly more challenging than the production of positive ions of the same element [3]. With the collinear resonance ionization spectroscopy (CRIS) experiment at ISOLDE, negative ions can be produced via double electron capture reactions in a charge exchange cell. Therefore, we plan to add a permanent spectrometer to the beamline where radioactive negative ions can be studied, specifically in the actinide region. The EA can be experimentally determined with laser photodetachment. At CRIS, we plan to observe the cross section of photodetachment in two ways. The residual neutral atoms can be detected or, depending on the electron configuration, a multi-step excitation scheme of laser photodetachment followed anium (U) [4]. After commissioning the spectrometer, EAs for polonium and francium will be among the first to be measured. Francium, the heaviest alkali metal, will require a two-step excitation scheme as mby resonance ionization can be used. Negative ion yield tests at CRIS have been carried out for urentioned above. This method has been successful for stable cesium (Cs) [5] and rubidium (Rb) [6]. In this contribution, results from the U-yield test, methods for alkali metal EA measurements, and the future spectrometer for negative ion studies at CRIS will be presented.
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2.25 High-resolution spectroscopy of exotic silver with a cw OPO injection-seeded PDA

Speaker: Mitzi Valeria Urquiza Gonzalez
Affiliation: HÜBNER GmbH & Co. KG, Kassel, Germany
Abstract: Short-lived radioisotopes are of special interest for nuclear structure studies, as their characteristic provide valuable reference points for theoretical predictions far from stability. By using lasers, hyperfine transitions can be accessed, allowing direct measurement of nuclear observables. For such high-resolution spectroscopy, narrow-band pulsed lasers can be created by the pulsed amplification of a cw seed laser, keeping the amplifier's high power and short time profile whilst acquiring the seeder's spectral properties. Spectroscopy on exotic Ag was performed at the CRIS experiment at CERN. A tunable cw single-mode OPO was employed as injection-seed for a two-stage pulsed dye amplifier. The hyperfine splitting of the ground-state $^2S_{1/2}$ to the level $^2P_{3/2}$ was measured and the hyperfine coupling constants were determined. For this work, ^{111,117}Ag are presented, showcasing this laser system's applicability for future high-resolution spectroscopy studies.

2.26 Recent results of nuclear spectroscopy for neutron-rich isotopes at KISS

Speaker: Momo Mukai
Affiliation: RIKEN

Abstract: The KEK Isotope Separation System (KISS) [1] was constructed to extract nuclei in the vicinity of $N = 126$ and ^{238}U produced by multi-nucleon transfer (MNT) reactions with the aim of elucidation of r-process nucleosynthesis. The KISS facility consists of an argon-gas-cell-based laser ion source combined with an isotope separator on-line, a $\beta - \gamma$ detector station, and a multi-reflection time-of-flight mass spectrograph (MRTOF-MS). The laser resonance ionization method is applied to ionize neutral atoms element-selectively at the exit of the gas cell. We have been conducting in-gas-cell laser resonance ionization spectroscopy, $\beta - \gamma$ decay spectroscopy, and mass spectroscopy of neutron-rich isotopes around $A \sim 190$. Recently, we've started to test the production of nuclides in the actinide region by using the MNT reactions between ^{238}U beam and ^{198}Pt target for future nuclear spectroscopy experiments. As a plan for the near future, we are going to perform in-gas-cell laser ionization spectroscopy of neutron-rich Hf and W isotopes to investigate the ground state shape evolution from the measured isotope shifts. The laser ionization schemes for both elements have been established, and the production of W isotopes with enough yields by using the MNT reactions between ^{136}Xe beam and $^{nat.}$Ir target was confirmed online so far. In the same nuclear region, the $\beta - \gamma$ spectroscopy of neutron-rich Ta isotopes was performed to investigate the properties of a K-isomer [2] and the ground state β-decay [3]. On the other hand, in the actinide region, we successfully extracted laser-ionized neutron-rich U and Np isotopes, and discovered a new neutron-rich uranium isotope, ^{241}U [4] for the first time in about 40 years. The extracted ions in the vicinity of W and U isotopes were analyzed in the MRTOF-MS for isobaric identification, and their atomic masses were successfully measured. In the presentation, we will present the results of nuclear spectroscopy of ^{187}Ta [3], neutron-rich W and U isotopes, and introduce the overview of the next generation of the KISS facility to study unexplored neutron-rich nuclei [5].

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2.27 Production of synthetic homogenous U-Pu samples for determination of rL-SNMS suppression rates

Speaker: Paul Hanemann
Affiliation: Institute of Radioecology and Radiation Protection, Leibniz University Hannover
Abstract: Resonant laser secondary neutral mass spectrometry (rL-SNMS) combines high elemental selectivity and spatial resolution. For ultra-trace analysis of isotopes like ^{238}Pu, non-resonant ionization of isobaric interferences, like ^{238}U, are challenging to remove. Reference material is needed for an investigation of the different ionization efficiencies of relevant elements. For rL-SNMS, such multi-element standards have specific requirements: homogeneity, be in a solid state, and with known isotopic composition. In this work we present a method for the production of homogenous U-Pu samples by fast Fe-coprecipitation. The homogeneity of the samples was confirmed by SIMS and EDX. The samples were used to determine the suppression ratios of non-resonant U in Pu rL-SNMS measurement. The presented method could be modified to produce homogenous sample material for other elements, and used to investigate relative ionization efficiencies for different elements.

2.28 Towards a high throughput ion source for MEDICIS

Speaker: Ralitsa Ivaylova Mancheva
Affiliation: KU Leuven BE
Abstract: 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 inside a metal tube which is heated to temperatures of up to 2200 degrees Celsius. This heating induces surface ionization from the walls of this so-called "hot cavity". If the overall ion load of laser and surface ionized species reaches a certain threshold, the confining potential which guides the created laser ions along the central axis towards the extraction field is compromised. Hence, efficient extraction of the created laser ions becomes impossible. This effect is especially prevalent in facilities like MEDICIS which demand a high ion throughput and fast extraction for collection of medical isotopes. This work will present the limits of the current laser ion source at ISOLDE and MEDICIS and introduce recent developments towards a new high throughput ion source.

2.29 Nuclear structure of Pd isotopes via optical spectroscopy

Speaker: Sarina Geldhof
Affiliation: GANIL
Abstract: High-resolution laser spectroscopy has been proven to be a powerful tool to extract nuclear structure data in an nuclear-model-independent manner. The isotope shift which can be extracted from the hyperfine spectra gives direct access to changes in mean-square charge radii, while the extracted hyperfine parameters give access to the nuclear spin, nuclear magnetic dipole moment and electric quadrupole moment. All this provides information on e.g. deformation and shape coexistence, proton-neutron pairing correlations, evolution of nuclear shells and the presence of shell closures. In recent years, measurements of nuclear ground state properties have also been proven exceptionally potent in testing state-of-the-art nuclear Density Functional Theory (DFT) and ab-initio approaches. The Pd isotopes are located in a transitional area in between chains which display smooth parabolic trends in the changes in mean-square charge radii (Sn, In, Cd and Ag), and a region where the changes in mean-square charge radii and corresponding electric quadrupole moments show evidence of a dramatic shape change at N=60, maximized and centred around the yttrium system. In the transitional area between both regions however, i.e. the Tc, Ru, Rh and Pd isotopes, no optical spectroscopic information has been available for radioactive nuclei so far. This is in part due to the refractory character of these nuclei, which makes their production challenging for many facilities, but also due to 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 and addition of a cw Ti:sapphire laser. Collinear laser spectroscopy was performed on unstable Pd isotopes, which are known to be deformed from decay spectroscopy studies, although there is disagreement on the origin and character of the (possible) change in deformation. The measured nuclear charge radii [1], spins and nuclear moments [2] will be presented in this contribution, and the implication on the deformation/shape of the isotopes will be discussed. In addition, the results will be compared to state-of-the-art DFT calculations using Fayans Energy Density Functionals (EDFs), and using Gogny EDF including beyond mean-field calculations within the Symmetry Conserving Configuration Mixing (SCCM) framework. As all recent benchmarks of nuclear DFT were performed on spherical systems, close to (doubly-)magic systems, this presents the first test of the performance of the Fayans functionals for well-deformed isotopes.
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2.30 Beta-delayed fission of neutron-rich actinides

Speaker: Silvia Bara
Affiliation: KU Leuven BE

Abstract: Beta-delayed fission (βDF) is a two-step process where a parent nucleus β-decays into one of the excited states of the daughter nucleus and when its energy is high enough with respect to the fission barrier, the process can end up with the fission of the daughter [1]. Besides its relevance in understanding the nuclear structure, βDF, as any other type of fission, may have a strong impact on the termination of the r-process. Unfortunately, the neutron-rich isotopes where this should happen are not accessible experimentally, so models based on experimental results must be developed to make predictions. βDF probabilities (PβDF) of currently accessible neutron-rich isotopes are several orders of magnitude smaller than their neutron-deficient counterparts. Therefore, most investigations of the βDF process have been performed on neutron-deficient cases where high-intensity beams of isotopes with a high PβDF are presently available. In order to widen the knowledge of βDF in the neutron-rich actinide region, a recent campaign was carried out at ISOLDE (CERN) with the purpose of measuring βDF in ^{230,232,234}Ac [2] (LOI216, May 2022). From this campaign upper limits for the βDF probabilities of ^{230}Ac and ^{232}Ac were preliminarily estimated, and the value for ^{230}Ac was found to be at least two orders of magnitude lower than the one reported in literature [3]. This contribution will discuss in more details the systematics of βDF, the preliminary results obtained during the LOI216 experimental campaign, and present some of the future plans of the βDF campaign.

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2.31 Influence of the temperature profile on ionisation in a surface ion source at ISOL@MYRRHA

Speaker: Sophie Hurier
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Abstract: MYRRHA [1] (Multi-purpose hYbrid Research Reactor for High-tech Applications) will be the world's first large-scale Accelerator Driven System at power levels scalable to industrial systems. In ISOL@MYRRHA [2], using part of the accelerated beam, Radioactive Ion Beams (RIBs) will be produced using the Isotope Separation On-Line (ISOL) technique, with increased isotope production through high intensity primary beam, over a long period. The aim is to maintain high-quality RIBs over that period. The surface ion source or hot cavity is chosen as initial source for its reliability and simple design, however the higher atom influx will affect its operation. This source was already studied theoretically and experimentally, by Kirchner [3] and by Huyse [4]. They have clearly identified temperature as a key element to this source's operation, typically assuming it to be constant along the cavity. To understand the hot cavity's behaviour, finite element thermal-electric simulations were performed with ANSYS [5,6,7]. In earlier work [6], thermo-electric simulations were validated and in the process a modified heating system was proposed, named ATS (Active Thermal Screen), one where a passive thermal screen is turned into an actively heated part. However, such simulations show that temperature is not constant along the ionising tube, but even subject to large variations. In this work, we will expand on the impact of the cavity temperature profile on surface ionisation parameters. The calculated thermal profile of the ATS showed a significantly reduced temperature drop at the hot cavity's end. A prototype of this novel hot cavity configuration has been constructed and is currently being tested at a heating test stand at SCK CEN.
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2.32 Challenges of Producing Terbium for Medical Applications

Speaker: Wiktoria Wojtaczka
Affiliation: KU Leuven BE
Abstract: Terbium ISOL Radioisotope for Medical Applications in Flanders (Tb-IRMA-V) [1] is a project funded by FWO under its Strategic & Basic Research program. A quadruplet of terbium isotopes has been identified to have complementary decay characteristics that have a unique potential to be used for both therapy and diagnostics for cancer treatment [2]. The project has three main objectives: reliable production of novel medical radioisotopes, their purification and handling, and demonstration of the valorization potential in the health sector. The radioactive species used for medical applications need to be isotopically pure which often requires mass separation [3]. There is a bottleneck when it comes to terbium production – it is challenging to extract from the target and ionize because of its high boiling point and its chemistry. So far, only Tb-155, which has a half-life of 5.32(6) days and can be used for SPECT imaging, has been collected at CERN-MEDICIS. The goal is to improve the collection efficiency and eventually be able to also produce the other isotopes, especially the alpha-emitter, Tb-149, which could fill the gap in the targeted alpha therapy but has a half-life of only 4.118(25) hours [4]. There are several factors that affect the efficiency of a radionuclide collection: the choice of the target material, the choice of the ion source, the mode of ionization, the operating temperature, as well the choice of material the sample is implanted into, amongst other factors. Most of the time all of those choices have to be carefully tailored not only to the element but specifically to the isotope of choice, which is evident when looking at collections performed at CERN-MEDICIS [3, 6, 7]. In order to be able to produce short-lived radionuclides, we need to understand how to extract and ionize them quickly and efficiently. In this contribution, we shall report on the experience gained at CERN-MEDICIS in the last few years.
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2.33 The shape of actinide nuclei as predicted by BSkG models

Speaker: Wouter Ryssens
Affiliation: Université Libre de Bruxelles
Abstract: The nuclear chart is an extraordinarily diverse place: atomic nuclei come in thousands of different species and the addition of a single nucleon can suffice to dramatically change their properties. One aspect of this rich phenomenology is their shape: the nuclear density in the intrinsic frame need not be spherically symmetric. The notion of a nuclear shape and its deformation underpins much of our understanding of low-energy nuclear structure and is particularly crucial to the modelling of nuclei with Energy Density Functional (EDF) methods. Models based on EDFs are currently the most microscopic theoretical tool that can be applied at scale, i.e. which is able to predict many different properties of thousands of (mostly heavy and neutron-rich) nuclei consistently within a single framework that describes a nucleus in terms of its constituent nucleons. The recent Brussels-Skyrme-on-a-Grid or BSkG models [1,2,3] describe essentially all known masses with a root-mean-square deviation better than 750 keV while *simultaneously* describing the systematics of charge radii, infinite nuclear matter properties, rotational properties and the known fission properties of actinides. In this contribution, I will introduce the BSkG models and talk about how they exploit the notion of a nuclear shape in particular and the concept of spontaneous symmetry breaking in general. I will further focus on the shapeof actinide nuclei as it is predicted by these models: starting with quadrupole deformation but moving on to more exotic octupole and hexadecapole deformation. Although the nuclear shape is not directly observable, I will detail how it impacts several different (pseudo-)observables, from nuclear charge radii to fission barriers and nuclear level densities. Time permitting, I will further specialize to one particular actinide nucleus: ^{238}U. This isotope, essentially stable and well-studied, is an archetype of the well-deformed rigid rotor and as suchs its shape is usually labelled as "well-understood". Recently however, the deformation of this nucleus was probed in an entirely new way: using ultrarelativistic collisions of ^{238}U ions at the BNL Relativistic Heavy Ion Collider (RHIC). State-of-the-art simulations of such collisions however fail to match precisely the experimental data. I will show that this failure arises from an incomplete accounting for the deformation of this nucleus: when correctly modeled, the shape of this nucleus as predicted by the BSkG-models is entirely consistent with the high-energy data. I will argue that RHIC (indirectly) observed the hexadecapole moment of ^{238}U [4].
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2.34 Kink in Mean-square Charge Radii of Tl Isotopes Studied by In-source Laser Spectroscopy at IDS/RILIS-ISOLDE

Speaker: Zixuan Yue
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Abstract: It is well-known that there is a kink in nuclear charge radii when the neutron number crosses a magic number [1]. This phenomenon has been observed in the Pb (Z=82) [2], Bi (Z=83) [3], and very recently, Hg (Z=80) [4] isotopes when crossing N=126 along their isotopic chain. However, the charge radii of Tl (Z=81) isotopes are only known up to ^{208}Tl (N=127). In order to determine whether such a kink is present in the Tl isotopic chain, at least one more isotope needs to be measured to differentiate it from the usual odd-even staggering in charge radii, where an odd-N isotope has a smaller charge radius than the average of its two even-N neighbours. In this contribution, I will present the results from a laser spectroscopy study of $^{205-209}$Tl (N=124-128) isotopes. Laser spectroscopy is a powerful tool for measuring electromagnetic moments and changes in charge radii of exotic nuclides. During the April 2022 experiment at ISOLDE, a combination of Resonance Ionization Laser Ion Source (RILIS) and ISOLDE Decay Station was used to measure the isotope shift and hyperfine structure of neutron-rich Tl isotopes, the study of which is usually hampered by strong, isobaric Fr contaminants. The RILIS in Laser Ion Source Trap (LIST) mode was applied to suppress such contaminations. The results establish a kink in the charge radii of Tl isotopes when crossing N=126, as well as providing the first measurements of the magnetic moments and charge radii of the 11/2- isomeric state of ^{207}Tl and the 1/2+ ground state of ^{209}Tl.
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2.35 Actinide quest at IGISOL

Speaker: Andrea Raggio
Affiliation: University of Jyväskylä
Abstract: Actinide isotopes have been enjoying a renewed interest over the past few years due to evidence for rich nuclear structure evolution, in particular in the neutron-deficient region, where theoretical models predict the most pronounced reflection-asymmetric shapes, see e.g., [1]. In addition, the actinides host some unique cases in which state-of-the-art atomic and nuclear theoretical models are challenged in their predictive capabilities. This is the case for the two well-known low-energy isomers in ^{229}Th and ^{235}U. 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 [2], University of Jyväskylä. The research focuses on the development of a range of production methods and the use of complementary spectroscopic techniques, including high-resolution laser spectroscopy, mass spectrometry, and $\alpha/\gamma/e^-$-decay spectroscopy. The former provides access to information such as the evolution of mean-square charge radii through the measurement of isotopic shifts in atomic transitions, in addition to nuclear electric quadrupole and magnetic dipole moments obtained via the atomic hyperfine structure [3]. Decay spectroscopy studies, on the other hand, provide a window to the measurement of decay modes and energies (Q values), branching ratio, half-lives, excited states, spins and parities and so forth, basic information that is often lacking in the region of interest. This contribution will present an overview of the experimental effort at the IGISOL facility, reporting on the development towards high-resolution laser spectroscopy of the low-energy ^{235m}U isomer, with a particular focus on the isomeric beam production [4]. In addition, the production and study of neutron-deficient actinide isotopes through the use of proton-induced fusion-evaporation reactions will be discussed. As a showcase, the result of a recent experiment using the new VADER spectroscopy station [5], dedicated to the study of decay properties in the region of interest, will be presented.
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2.36 In-gas-jet laser spectroscopy with S3-LEB

Speaker: Anjali Ajayakumar
Affiliation: Ganil

Abstract: The Superconducting Linear Accelerator (SPIRAL2-LINAC) facility of (GANIL) extends the capabilities of studying exotic nuclei by producing beams of rare radioactive isotopes with the highest intensities so far produced [1,2]. The SPIRAL2-LINAC coupled with Super Separator Spectrometer (S3) recoil separator will facilitate the production of neutron-deficient nuclei close to proton dripline and super heavy nuclei via fusion evaporation reactions and separate them from the intense background contamination [3]. The Super Separator Spectrometer-Low Energy Branch (S^3-LEB) is a low-energy radioactive ion beam experiment under commissioning as part of the GANIL-SPIRAL2 facility. It will be used for the production and study of exotic nuclei by in-gas laser ionization and spectroscopy (IGLIS), decay spectroscopy, and mass spectrometry. Development work has been ongoing at the S3-LEB setup [4, 5]. We report recent results from the off-line commissioning of S^3-LEB, including first laser spectroscopy measurements in both the gas cell and the supersonic gas jet, the determination of the transport efficiency of laser ions from the gas cell through the RFQ chain, and time-of-flight measurements with the multi-reflection time-of-flight mass spectrometer PILGRIM.

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3 Posters

3.1 Optimization and development of RFQ Cooler Bunchers for S3-LEB and JetRIS

Speaker: Alexandre Brizard
Affiliation: GANIL
Abstract: The superconducting Linear Accelerator (SPIRAL2-LINAC) coupled with the Super Separator Spectrometer (S3) will allow GANIL to produce neutron-deficient and super heavy nuclei via fusion evaporation reactions. At the focal plane of S3, the S3-Low Energy Branch (S3-LEB) setup will stop and neutralize the exotic ions before performing in gas jet resonant laser ionization that would allow accessing some fundamental properties of the nuclei. Moreover, this highly selective and efficient technique will produce a pure beam on which further measurement will be possible. Among these, a mass measurement by a Multi Reflection Time Of Flight Mass Spectrometer (MR-TOF-MS) will be performed. JetRIS is the successor of the Radiation Detected Resonance Ionization Spectroscopy (RADRIS) setup in GSI. RADRIS performed resonance ionization in the gas cell before guiding the ions thus produced to an alpha detector. JetRIS is also using resonant ionization spectroscopy, but the technology is similar to the one chosen for S3-LEB as it is performed in a hypersonic gas jet to overcome the pressure and Doppler broadening in the gas cell, and to extract the ions faster so that it can detect shorter lived nuclei. From now on, the beam produced by the resonant ionization is studied using an alpha detector. It is foreseen to install an MR-TOF-MS to enhance the possibilities of the setup by practicing high precision mass measurement. Both setups will make use of an MR-TOF-MS, which requires the incoming beam to be bunched. For this, a Radio Frequency Quadrupole Cooler Buncher (RFQcb) has already been designed and is currently commissioned with the S3-LEB setup. This commissioning will make use of ions trajectory simulations to get the best transmission possible during the bunching process and then compare these simulations to experimental results. Bunching unit is yet to be designed for JetRIS setup, forecasting a similar design to that of S3-LEB. Here, we present the incoming work on the RFQcb simulations to improve the efficiency for S3-LEB in GANIL, and on the design for the new RFQcb to be commissioned in GSI for JetRIS.

3.2 ACORN (Alkali-earth ions Confined for Optical and Radiofrequency spectroscopy for Nuclear moments)

Speaker: Anais Dorne
Affiliation: KU Leuven BE
Abstract: Nuclear moments have proved to be excellent probes for nuclear configurations, acting as excellent benchmarks for nuclear theory. Having only been measured on 20 stable isotopes, the magnetic octupole moment is a promising observable for the study of magnetization currents and nucleon distribution. I present the construction of ACORN (Alkali-earth ions Confined for Optical and Radiofrequency spectroscopy for Nuclear moments), a new Paul trap experiment for the measurement of the nuclear magnetic octupole moment of alkali-earth ions. I discuss the trap design, tailored to perform magnetic octupole measurements of stable isotopes, and highlight the challenges related to extending studies to radioactive isotopes. I also discuss the choice of the first element the ACORN experiment will be performed on, the general principles of the measurement scheme, and the laser system associated to it.

3.3 Precision laser spectroscopy of short-lived bismuth isotopes

Speaker: Anita Candiello
Affiliation: KU Leuven
Abstract: The nuclear electromagnetic moments (EM) and the mean-charge radius are important properties useful to investigate the nuclear structure and to probe our understanding of the nucleon-nucleon interaction. While the former gives an indication of the charge and current distribution in the nucleus, the radius allows to evaluate its size. Measurements of the lowest order EM moments and of the radius can be obtained with laser spectroscopy, a widely used experimental method which probes the hyperfine structure of atoms. Part of my PhD research will be devoted to the study of multi-quasiparticle (mqp) isomers. All measurements on mqp isomers so far have determined them to have smaller radii, even though they possess larger quadrupole moments [1,2]. A theoretical interpretation of these observations is essentially lacking. Because Bi isotopes have only one valence proton outside the double-closed shell of ^{208}Pb, their configurations are rather pure. Thus, the single-particle and collective degrees of freedom in the radii and moments are better under control. I will use the RAPTOR beamline, a recently developed setup, to measure the electric quadrupole moment and the mean charge radius of all short-lived states in $^{204-208}$Bi (half-life between 13 ms and 182 s). Comparison of the results with the nuclear theory models could allow to understand the puzzling reduction in the nuclear charge radius of multi-quasiparticle isomers with respect to the ground state. In this contribution, I will provide an overview of the current status of the RAPTOR setup. An outlook towards the planned measurements on bismuth will be given.
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[2] Boos, N., et al., "Nuclear Properties of the Exotic High-Spin Isomer ^{178}Hf^{m2} from Collinear Laser Spectroscopy", Physical Review Letters 72.17 (1994) 2689-2692

3.4 Development of new Decay Spectroscopy Station at CRIS

Speaker: Bram Van Den Borne
Affiliation: KU Leuven BE
Abstract: Laser spectroscopy can study many ground-state properties (spin, nuclear electromagnetic moments, changes in the charge radius) of the nucleus which can challenge state-of-the-art nuclear models, and enhance our understanding of the nuclear forces. Furthermore, its application at ISOL facilities can give access to the same properties of long-lived states (>10ms). One major challenge that laser spectroscopy at ISOL facilities face is the presence of isobaric contaminants that can increase the background signal significantly. This background can completely dominate the measured spectra for low-yield isotopes, thus making these isotopes inaccessible. The Decay Spectroscopy Station (DSS) can solve this problem by combining laser and decay spectroscopy in decay assisted laser spectroscopy, which can tag the isomer of interest based on its decay. Experimental work on previous designs of the DSS at ISOLDE/CERN has been performed successfully on neutron-rich potassium (*Z*=19) [1] and francium (*Z*=87) [2-4]. Conversely, laser assisted decay spectroscopy can also be performed with the DSS at CRIS by tagging the isomer of interest based on its ionisation scheme. This was successfully performed with a previous design on francium (*Z*=87) [3-4]. Recently there is an effort to upgrade the previous design of DSS to include a tape station and a dedicated beta-detection setup. I will present this new design and the upgrades implemented compared to the previous designs. Simulations of the beta detection of the new design are made and will be presented together with the results from the commissioning in this contribution.
References:
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3.5 Production analysis of Fr, Ra and Ac isotopes at CERN-ISOLDE

Speaker: Erika Jajčišinová
Affiliation: KU Leuven BE
Abstract: The production of heavy radionuclides at radioactive ion beam facilities has an impact on many fields, including decay and laser spectroscopy studies, β-delayed fission of actinides, nuclear structure studies, but also nuclear medicine. In recent years, the use of alpha emitters for targeted alpha therapy (TAT) has proven to be a very promising tool for cancer treatment. Specifically, the ^{22} Ac isotope showed better efficacy, compared to ^{1} Lu, with its higher linear energy transfer and the use of 1000 times less radioactivity for the same treatment. Because of this, demand increased unequally with production. Several methods of production are being investigated. One of them is the production of radioactive ion beams (RIB) by the isotope separation online (ISOL) technique. At CERN, in the ISOLDE facility, this process relies on the reaction of highly energetic protons (1.4 GeV) impinging on the thick target, in this study Uranium Carbide, inducing nuclear reactions, mainly fission, spallation and fragmentation. The process of getting these isotopes out of the target is complex and consists of multiple steps. Diffusion is the first step, followed by effusion and ionization (e.g., with the last step, one can enhance RIB yield using laser ionization). In facilities that operate pulsed beams, a release curve describes the time-dependent isotope release profile based on 4 empirical parameters. These parameters stay the same for the isotopic chain but differ within elements, target material compound and respective microstructure and also the operating temperature. With this knowledge, one can determine the yield of the isotope and derive relative efficiency across different isotopes (half-lives) of the same element. The presented work contains the release parameters of Fr, Ra and Ac and the yields related to them retrieved at the ISOLDE facility at CERN.

3.6 Development of fundamental/second harmonic generation mode switching and beam path control system of grating Ti:Sapphire laser for rapid multi-element/isotope analysis

Speaker: Hiroki Miura
Affiliation: Nagoya University
Abstract: Characterization of fuel debris properties is required to proceed decommissioning of the Fukushima Daiichi Nuclear Power Plant. Toward micro-isotope imaging of fuel debris containing fission products and actinide isotopes, we are developing a resonant laser Secondary Neutral Mass Spectrometry (SNMS) using a high repetition rate grating Ti:Sapphire laser. In this study, the fundamental/second harmonic generation mode switching and beam path control system of the grating Ti:Sapphire laser was developed for quick change of resonance ionization schemes in multi-element/isotope analysis with resonant laser SNMS.

3.7 Synthesis of a tailored thorium based structure for the ISOL@MYRRHA target to produce and release Ac225

Speaker: Lisa Gubbels
Affiliation: SCKCEN & KULeuven
Abstract: Isotope separation online (ISOL) facilities produce radioactive isotope beams that are purified and used in physics and medical research. At SCK CEN, the first phase of the MYRRHA program consist on building a new ISOL facility with a high power proton beam of 100 MeV and up to 500 A. This will allow to produce medical research radioactive isotope beams such as ^{225}Ac (among others), which is one of the most desired isotopes in cancer research in the past decade. In this work, we focus on the production of ^{225}Ac by using a Th-based target. The structural properties of the target compound (ThO_2 or ThC_x) should be tailored to fulfill requirements that favor isotope release; e.g. micrometer pore size, low density, open porosity and tailored grain size. In particular, our first focus is on the ThO_2 powder preparation in which we compare three precipitation routes i.e. hydroxide, homogeneous oxalate and heterogeneous oxalate which provides respectively nanoparticles, micrometric cubic particles and platelet structures, and on the thoria powder pelletization behaviour. After complete characterization, the best structure will be selected to build a ThO_2 target and used to produce a ThC_x target. In this contribution, we will present the comparison between the three powder synthesis routes for producing ISOL targets and draw preliminary conclusions of our ongoing work.

3.8 Is self-sputtering worth considering for isotope implantations?

Speaker: Marie Helena M Deseyn
Affiliation: KU Leuven BE
Abstract: CERN MEDICIS [1] is a facility that produces radionuclides for medical research. It uses the mass separation technique to produce a pure radioactive ion beam that is subsequently implanted onto a coated foil. During the collection of radionuclides, each radioisotope counts and thus the amount of atoms, and therefore the amount of collected activity, should be maximized. Via an online monitoring of the activity being implanted onto the foil (which recently became possible using a Kromek CZT detector), it has been observed that some activity of the previously collected radionuclide was remaining in the collection chamber after the removal of the foil. It was suggested that this is caused by self-sputtering. Self-sputtering occurs when the momentum of the impinging ion is transferred to nuclei in the collection foil, causing a nuclear collision cascade that can eject surface nuclei, i.e., these nuclei are sputtered out of the foil. As the implantation is started, the foil material nuclei will be sputtered out of the foil, hence the surface of the foil will approach the earlier implanted isotopes. Consequently, these earlier implanted isotopes eventually reach the surface, so that they can be self-sputtered from the foil. The main aim of this work was to investigate the self-sputtering behaviour of nuclei ranging from medium to heavy masses (Z=21 to Z=89) for implantation into foils coated with a metallic layer (Al, Zn), a salt layer (NaCl, $NaNO_3$), and into sugar derivatives using the simulation software TRIDYN [2, 3, 4]. The results provide essential information for improving the collection efficiency. This is crucial to overcome the fundamental limits imposed by self-sputtering in order to scale up medical isotope production, at CERN MEDICIS today, but also at new facilities such as ISOLPHARM (Italy) [5] and ISOL@MYRRHA (Belgium) [6]. Experiments will be performed to benchmark the results from the TRIDYN simulations in the case of implantation of Yb onto Zn and Al. Additionally, for -decaying nuclei like ^{149}Tb or ^{225}Ac, during transport to e.g., hospitals not only are isotopes lost due to the decay but also due to recoil-sputtering. Here, the recoiling daughter nucleus traverses the foil and transfers its energy to surrounding particles, upon which earlier implanted isotopes can be sputtered away in the same way as with an impinging ion beam. For example, subsequently to the collection of 225Ac collection of December 2022 at CERN MEDICIS, -decay spectroscopy was performed and about 0.087Bq was recoil-sputtered after 21 days, which corresponds to 0.0008% of the total activity at the start.
References:
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3.9 Resonance Ionization Mass Spectroscopy on Americium

Speaker: Matou Stemmler
Affiliation:
Abstract: Americium (Am, Z=95) is a transuranic member of the actinide series and was discovered in 1944 by the group led by Glenn T. Seaborg. The two most long-lived americium isotopes are ^{241}Am with a half-life of $t_{1/2} = 432.2$ a and ^{243}Am with a half-life of $t_{1/2} = 7370$ a. As any primordial americium has decayed by now, these isotopes are produced artificially by neutron irradiation, also in nuclear power reactors. One ton of spent nuclear fuel contains about 100 g of americium. Applications for americium have been proposed, e.g., as fuel for spaceships with nuclear propulsion, and ^{241}Am is routinely used today in ionization-type smoke detectors and - when mixed with beryllium - as a neutron source. The accumulated knowledge on atomic and nuclear properties in literature is rather scarce and only very limited fundamental atomic and nuclear data obtained in optical spectroscopic studies have been reported to date. Resonance ionization spectroscopy (RIS) was used as a very sensitive technique to precisely study atomic excitation schemes and level positions in the spectrum of americium, both for fundamental studies as well as in preparation of laser mass spectrometric ultra-trace analysis. We report on two-step high resolution RIS in Am at the RISIKO off-line radioactive ion beam facility. About 10^{13} atoms of both isotopes ^{241}Am and ^{243}Am each were prepared on zirconium foil and loaded into a resistively heated tantalum oven. A wide-range tuneable, frequency doubled, continuous wave Ti:sapphire laser was used for spectroscopy by injection locking of a high power pulsed Ti:sapphire ring laser setup. Hyperfine structures of the two isotopes ^{241,243}Am were investigated in two different ground state transitions at 23437.0 cm^{-1} and 25409.5 cm^{-1}, which served as first excitation steps for resonant ionization via suitable autoionizing states. In addition, the isotope shift was measured for both isotopes. Results regarding the atomic structure of Am as well as extracted hyperfine parameters will be discussed.

3.10 Developments in muonic x-ray spectroscopy

Speaker: Michael Heines
Affiliation: KU Leuven - IKS
Abstract: Muonic x-ray spectroscopy is a technique that utilizes the properties of the muon to obtain information about the structure of the atom and the nucleus. When a muon interacts with an atom, it can be captured in a high principal atomic quantum number state, after which it will fall towards the ground state emitting high energy characteristic x rays. Due to the heavy mass of muons compared to that of electrons ($m_\mu \approx 207 m_e$, the muon's orbitals are closer to the nucleus with that same factor. Hence, the muonic energy levels are more sensitive to nuclear effects. In particular, the finite size correction is increased by a factor close to 10^7. Consequently, muonic x rays can provide valuable input for laser spectroscopy in the form of high-precision absolute charge radii (10^{-3} relative precision). While muonic x rays have been extensively studied at the end of the twentieth century, it was limited to target quantities above 10 mg. However, in 2017, our collaboration investigated the use of a high-pressure hydrogen cell with a small deuterium admixture in order to enhance the transfer of the muon to the target atom of interest [1]. With this advancement, measurements on targets of 5 µg became possible, opening the door to long-lived radioactive isotopes (>20 years) [2]. At low-to-medium atomic numbers, a high isotopic purity is required in order to reliably extract the nuclear charge radius. This purity can only be obtained by using magnetic mass separation for certain isotopes. Therefore, we investigated the feasibility of using implanted targets during a beamtime in September 2022. Besides measurements on implanted targets, the attenuation of the muonic x-ray signal through graphite was quantified. These advancements will allow for absolute charge radii measurements on materials that are not available in sufficiently large quantities and/or isotopic purity. In this contribution, we will report on the recent advancements of the muX collaboration as well as their implications for future research.
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3.11 Design and simulations of a linear Paul trap for single-ion spectroscopy

Speaker: Stefanos Pelonis
Affiliation: KU Leuven
Abstract: To understand the key behaviors of the atomic nucleus, tremendous effort over the past decades has been put on ab-initio theoretical models [1], which are able to reproduce experimental data with great accuracy. To better benchmark such models, various observables need to be measured, with important ones being, for example, the nuclear electromagnetic moments and charge radii. Measurements of these quantities can be obtained using different techniques, but a very successful one has been Laser Spectroscopy. To extend measurements to more nuclei, previously unexplored due limited sensitivity, and to achieve higher precision spectroscopy, we plan to study ions trapped in a segmented linear Paul trap, designed and optimized inside SIMION 8.1 [2]. This scheme will substantially increase the laser-ion interaction time, offering higher sensitivity over hyperfine structure precision spectroscopy measurements. Simulations have been performed assuming properties of typical ISOLDE beams, to study the injection, deceleration and dymanic capture of the ions, without buffer gas. Subsequent Doppler laser cooling down to the Doppler limit was simulated, with the aim to reduce the Doppler broadening below the natural linewidth. The results indicate that the trapping and cooling schemes can be performed with around 60 % capture efficiency, in a few 100 ms, paving the way to the study of e.g. octupole moments on radio-nuclides. The configuration of this trap could also be extended for sympathetic cooling of trapped species [3] and/or radio-frequency spectroscopy using forbidden transitions [4]. Construction of the trap setup will begin this autumn, as part of my PhD.
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3.12 Results from offline and online commissioning test of the upgraded CRIS beam line

Speaker: Yazeed Balasmeh; Juan Trujillo Garcia
Affiliation: Yazeed Balasmeh KU Leuven; Juan Trujillo Garcia KU Leuven BE
Abstract: The collinear resonance ionization spectroscopy (CRIS) setup at ISOLDE (CERN) [1] is a powerful apparatus which delivers measurements of nuclear properties (spin, electromagnetic moments and charge radii) for exotic nuclei with high resolution and efficiency. The nuclear information is extracted from studying the atomic hyperfine structure, which is measured by detecting resonantly ionized atoms (or molecules) as a function of the laser frequency. This can be achieved by applying a multi-step ionization scheme, where the atomic bunch is overlapped by several laser beams to resonantly excite the atom. The first high-precision resonant step is followed by an ionization step induced by a high-power laser. The ions are then separated from the neutral particles by deflecting them towards an ion detector. Applying this method results in low background rates due to the low probability of non-resonant ionization processes and thus a very high sensitivity. However, when weakly produced isotopes are studied in the presence of large isobaric contamination, the non-resonant background rate becomes significant. A solution is to use a novel electric field-ionization chamber [2] to field-ionize. The atoms that are resonantly excited using a two-step scheme into a Rydberg state, using low-power lasers. This reduces the probability for non-resonant ionization of the contaminating species, and thus the background ions. A new quadrupole triplet is also installed for focusing and steering the ion beam onto the ion detector. The performance of this setup will be investigated, through offline and online commissioning test.

3.13 VUV spectroscopy of the radiative decay of ^{229m}Th: calibrations, background studies, and simulations

Speaker: Yens Elskens
Affiliation: KU Leuven
Abstract: Due to its low excitation energy around 8 eV, the unique ^{229}Th isomer is a possible candidate for developing a nuclear clock for, amongst others, fundamental physics studies. In the past, measuring the isomer's radiative decay from a large-bandgap crystal with ^{229m}Th embedded, has proven difficult: the commonly used population of the isomer via the ^{233}U α-decay has a limited branching ratio towards the isomer and creates a high-radioluminescence background. However, recently, a new approach to populate the isomer through the β-decay of ^{229}Ac was proposed. This approach made it possible to observe, for the first time, the radiative decay of the ^{229}Th isomer with vacuum-ultraviolet (VUV) spectroscopy, which allowed to successfully determine the resulting photon's wavelength. Building on this work, the VUV spectrometer has been upgraded in view of a new measurement campaign, which aims to reduce the systematic uncertainty and to accurately determine the half-life of ^{229m}Th, embedded in different crystals under different conditions. This work presents the calibrations, background studies, and simulations performed as a preliminary step in this measurement campaign.