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The SCRIT electron scattering facility at the RIKEN RI Beam Factory

Invited
3 Oct
9:00am

Tetsuya Ohnishi[1], Yasushi Abe [1], Akitomo Enokizono [2], Taiga Goke [3], Masahiro Hara [1], Yuki Honda [3], Toshitada Hori [1], Shinichi Ichikawa [1], Kazuyoshi Kurita [2], Clement Legris [3], Yoshiki Maehara [4], Ryo Ogawara [5], Toshimi Suda [3], Tadaaki Tamake [6], Kyo Tsukada [4], Masanori Wakasugi [7], Masamitsu Watanabe [1], Hikari Wauke [8]

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Electron scattering is a powerful tool for studying nuclear structure, and it has been long-awaited for unstable nuclei, because it allows model-independent studies of nuclear structure, including fundamental parameters, such as size and shape. After many years of development, the world's first experiment on electron scattering off unstable nuclei is, recently, finally ready at the SCRIT (Self-Confining Radioactive isotope Ion Target) electron scattering facility [1] at the RIKEN RI Beam factory using a novel target forming technique, SCRIT. [2]

The SCRIT facility consist of a compact racetrack microtron, an electron storage ring equipped with the SCRIT system, an online isotope separator (ERIS), and a dc-to-pulse beam converter. RI beams produced at ERIS are converted to pulsed beams and injected to the SCRIT system. RIs trapped inside the SCRIT system play as stationary targets and electron beam stored in the ring are scattered from the RI targets. An electron spectrometer besides the SCRIT system analyzes the momentum and the trajectories of scattered electrons. The luminosity is measured continuously by a luminosity monitoring system placed at the downstream exit of the straight section of the electron storage ring. The usefulness of the SCRIT was demonstrated in the commissioning experiment. [3]

At ERIS, the RI production using the photofission of uranium is performed with the self-made UCx target. For instance, the rate of ^{132}Sn and ^{137}Cs are reached as 2.6×10^5 ions/sec and 1.2×10^7 ions/sec, respectively, with the 15-W electron beam irradiation on the UCx target including 28-g uranium. For ^{137}Cs case, the luminosity is expected to reach about 2×10^{26} $cm^{-2}s^{-1}$, even at such a low production rate. In addition, there are plans to upgrade the electron beam power to 2 kW for electron elastic scattering from ^{132}Sn.

In this contribution, we will introduce the SCRIT electron scattering facility and report the present status, the upgrade plan, and the progress of the experiment with unstable nuclei.

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Nucleosynthesis in Multinucleon Transfer Reactions

Invited
3 Oct
9:30am

Sophia Heinz

For decades, fragmentation, fission and fusion reactions are versatile tools to produce exotic nuclei in the lab. However, these standard nucleosynthesis reactions are reaching their limits. To enter new territory on the chart of nuclides, new pathways to exotic nuclei are needed. Mainly on the neutron-rich side, several thousand further isotopes are expected to exist, including most of the nuclei along the astrophysical r-process path.

Years ago, the idea arose to "revive" multi-nucleon transfer reactions to progress toward the neutron rich side of heavy and superheavy nuclei. Meanwhile, this option is investigated in nuclear physics labs worldwide. Beside new studies of transfer product kinematics and cross-sections, the development of suitable separation and detection techniques for heavy transfer products is ongoing. How promising are these new advances? So far achieved results allow us to get an impression on the potential which multi-nucleon transfer reactions provide for nucleosynthesis.

3 Oct
10:00am

Multi-element beam delivery with the TRIUMF resonant ionization laser ion source

Jens Lassen[1], Ruohong Li [2], Maryam Mostamand [2], Peter Kunz [2], Alexander Gottberg [2]

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The resonant ionization laser ion source (RILIS) has developed into a reliable ion source that allows to ionize a majority of the elements. At TRIUMF's radioactive ion beam facility ISAC - which is short for Isotope Separator and Accelerator facility, a thick isol target is subjected to a primary proton beam from TRIUMF's 500MeV cyclotron for isotope production through fragmentation, fission and spallation. The isotope production target station can receive up to 100uA of protons onto target materials up to 238U. The radioactive isotopes produced need to be ionized in order to be extracted and delivered to experiments. The ion sources available at ISAC are a surface ion source, a gas discharge ion source and a resonant ionization laser ion source. One of the key characteristics of resonance ionization is its element selectivity, its versatility, and high efficiency. By now isotopes from 41 different elements have been ionized with the TRIUMF RILIS, and ionization schemes for another 22 elements have been developed off-line on stable isotopes. Current developments for RILIS aim for higher reliability, shorter setup and switch over time between elements, higher efficiency and improved suppression of non-laser ionized isobars. One way of achieving improved RIB delivery to experiments has been to set up laser ionization of two elements, so that experiments can switch between, laser on/off operation and laser ionization of two different elements. Another operation mode is concurrent laser ionization of two different elements - which is an operation mode that is particularly useful for 225Ac and 225Ra isotope collections.

I will present and discuss several examples of multiple element beam delivery at ISAC for experiments that were conducted in recent years and the instrumental and operational boundary conditions.

Prospects for high resolution in-source spectroscopy using cross laser / atom beam geometry: Nuclear structure investigation on actinium isotopes with ISOLDE's new ion source PI-LIST

3 Oct
10:20am

Reinhard Heinke[1] for the IS664/IS456/PI-LIST collaboration

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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, and a clean laser-atom interaction region in an RFQ unit 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 reduces the effective Doppler broadening by addressing only the transversal velocity components of the effusing atom ensemble.

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 were probed, pinning down predictions of recent Energy Density Functional nuclear theories that incorporate reflection symmetry breaking [7].

Results of this experimental campaign, the applicability of the technique to ISOL facilities in general, its limits especially in terms of efficiency, and technical implementation challenges are discussed.

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Invited
3 Oct
11:10am

Targets for In-Flight Separators with Intense Beams

Helmut Weick[1]

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Production of rare ions from projectiles in flight is a universal technique for most nuclides. Besides fragmentation and fission in-flight also fusion and multi-nucleon transfer can be used for production. A separator is needed before inflight identification of ions and experiments can follow.

With more intense beams the first challenge is the target itself, because heavy ion beams lead to a high density of energy deposition. Cooling mechanisms need to be integrated and radiation damage be considered. Mechanical stress is another limit which especially becomes sever as dynamic stress in case of pulsed beams.

The basic parameters for optimisation of yields will be discussed, with respect to production cross sections, target thickness, energy-loss in the target as a limiting factor. The latest high intensity facilities BigRIPS/RIKEN, ARIS/FRIB, Super-FRS/FAIR, S3/GANIL, HFRS/HIAF, IF/RAON are good examples.

It is the direct integration into an isotope separator which causes most difficulties. The systems have to work in vacuum as with the intense beam vacuum windows are usually ruled out. The separator must be designed in such a way that intense beam must not hit a normal vacuum chamber but only dedicated beam catchers. As the expensive separator should be versatile for many nuclides, the remaining primary beam can hit many positions and due to a different magnetic rigidity will also be focused differently than the wanted fragment beam. All this has to be considered in the design of the separator. Contrary to dedicated beam dumps for production of only one particle species at one fixed energy the design becomes much more complicated. It will be shown in the case of Super-FRS.

It also means handling of the components hit by intense beams have limited lifetimes and require a bigger infrastructure for handling of radioactive parts around it, as will be shown in the case of Super-FRS.

Operational experiences of high-power production target and high-power beam dump at BigRIPS separator at RIKEN RI beam factory

3 Oct
11:40am

Koichi Yoshida[1], Yoshiyuki Yanagisawa [1], Masao Ohtake [1], Toshiyuki Kubo [1]

[1] *RIKEN*

A water-cooled rotating target and a water cooled stational beam dump to withstand beam powers of 82 kW corresponding to the ^{238}U beams with the energy of 345 MeV/nucleon and the intensity of 1 particle μA, were developed as the target and beam dump system for the BigRIPS separator at RIKEN RI Beam factory in 2007. They have been successfully operated without sever trouble with the beam powers of up to 15 kW. Operational experiences of these systems over the 15 years will be presented at the conference. Results of measurements of the beam-spot temperatures for the target and the beam dump with various beams from RIBF accelerators were compared with the thermal model calculations and validity of the design will be discussed. Radiation damage to the system equipment, although not yet relevantly observed, will also be discussed along with PHITS[1] simulation results.

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3 Oct
12:00pm

Improved isotope intensity and purity from a new spallation-driven proton-to-neutron converter at ISAC-TRIUMF

Alexander Gottberg[1], Luca Egoriti[1], Thomas Day Goodacre[1]
[1] *TRIUMF*

A spallation-driven, proton-to-neutron converter target has been developed and irradiated at the ISAC-TRIUMF facility, focusing on the production of radioactive ion beams (RIBs) of neutron-rich fission fragments and limiting by design the production of their neutron-deficient isobaric contaminants. So far, fission fragment RIBs have been produced at ISAC-TRIUMF with the ISOL method by impinging the incoming proton beam onto a 10-cm stack of hundreds of closely packed actinide composite foils in a cylindrical tantalum oven. One important issue that users experience is the presence of neutron-deficient isobaric contamination that frequently dominates the beam of interest and prevents the successful outcome of the experiment. A new proton-to-neutron converter target assembly has been designed with the intent of reducing the in-target production of neutron-deficient isobaric contaminants by generating an intense spallation neutron field from a tungsten converter, positioned just downstream of an annular uranium carbide target. The fast neutrons subsequently induce fission reactions in the actinide material, producing predominantly neutron-rich radioisotopes while limiting the production of the neutron-deficient, spallation-induced reaction products. In addition to the different distribution of produced isotopes, a thermal decoupling between the target and converter components, as well as the reduction of long-lived and highly radiotoxic alpha emitting isotopes offer additional benefits that allow high-power irradiations and more efficient isotope release.

This contribution presents the combined numerical and experimental optimization process that led to the final target design and focuses on the successful online results obtained at the ISAC-TRIUMF facility from several independent irradiation campaigns. The extensive online beam time dedicated to this target has allowed for precise characterization of its performance by exploring a wide parameter space and has already allowed the delivery of more exotic neutron-rich isotope beams of Rb, Cs, Zn and Ga, enabling successful completion of previously unfeasible experiments. Further investigations of Sn isotopes are planned for the summer of 2022.

Precision laser spectroscopy of fast radioactive beams and trapped ions

Invited
3 Oct
2:00pm

Ruben de Groote[1]
[1]*KU Leuven*

Laser spectroscopy techniques provide nuclear-model independent access to nuclear electromagnetic moments, spins and charge radii. Advances in radioactive ion beam instrumentation and laser technologies have enabled the study of a wide range of elements and isotopes, pushing out far from the valley of stability towards the drip lines.

In this contribution, I will present experimental progress along several important frontiers in the field. I will discuss the use of methods based on laser ionization spectroscopy and how they have allowed us to reach exotic nuclei such as 96Ag or 52K. Crucially, these measurements relied on the use of decay detection or ultra-selective mass separation tools to provide low-background measurement conditions.

Besides using efficient laser ionization and particle detection methods, another important area of research relies on the use of ion traps. I will show a recent example of how ions trapped in a linear Paul trap can be optically pumped into a beneficial metastable state. In particular, I will show how this approach enabled fluorescence spectroscopy of neutron-deficient singly-charged cobalt isotopes. Finally, I will conclude with a discussion of future avenues for spectroscopy, which entail doing optical and radiofrequency spectroscopy of radioactive ions while they are trapped in a linear Paul trap.

3 Oct
2:30pm

Development of Ti:sa laser ion sources for S3-LEB at SPIRAL2-GANIL

Jekabs Romans[1], Alejandro Ortiz-Cortes [2], Anjali Ajayakumar [3], Antoine de Roubin [4], Arno Claessens [4], Dominik Studer [5], Herve Savajols [2], Iain Moore [6], Klaus Wendt [7], Lucia Caceres [3], Nathalie Lecesne [3], Pierre DELAHAYE [2], Piet Van Duppen [8], Rafael Ferrer [4], Renan Leroy [2], Ruben de Groote [4], Sarina Geldhof [3], Sebastian Raeder [9], Serge Franchoo [10], Simon Sels [4], Vladimir Manea [10], Wenling Dong [10], Xavier Flechard [11], Yazeed Balasmeh [12]

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At GANIL-SPIRAL2 and LPC Caen the Super Separator Spectrometer-Low Energy Branch (S^3-LEB) [1] project is under development to study exotic nuclei by In-Gas Laser Ionization Spectroscopy (IGLIS) to extract ground-state properties, such as nuclear mean-square charge radii $< r^2 >$, magnetic dipole μ and electrical quadrupole Q moments, and nuclear spins I. The nuclides of interest will enter a gas cell where thermalization and neutralization will take place under a constant gas flow. A supersonic gas jet will be created by a de Laval nozzle with a high Mach number M [2], resulting in a collimated low-temperature and low-density environment, where IGLIS will be subsequently performed. The in-gas-jet laser spectroscopy method will result in higher spectral resolution without loss in the efficiency in comparison to the in-gas-cell spectroscopy studies [3].

A crucial aspect of the S^3-LEB setup is the laser system, which has been extensively developed at GISELE offline laser laboratory for the purpose of performing mid- to high-resolution spectroscopy [4]. Having multiple laser systems with different resolving powers is necessary for performing measurements either in-gas-cell or in-gas-jet environments. In order to resolve hyperfine structures and extract nuclear properties of interest, one requires wide scanning range, narrow spectral linewidths, adequate temporal and spatial laser overlap and reliable recording of the measurement parameters. The progressive development of the titanium:sapphire laser systems in our laboratory has led to successful measurements of a few elements of interest for the day-1 experimental program like erbium, tin and palladium. This development work and latest laser-spectroscopy results will be presented.

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3 Oct
2:50pm

Advances at the CRIS experiment for the laser spectroscopy of short-lived radioactive atoms and molecules

Michail Athanasakis-Kaklamanakis[1], Mark L. Bissell [2], Mia Au [3], Anastasia Borschevsky [4], Anais Dorne [5], Aleksandra A. Kiuberis [4], Agota Koszorus [6], Adam Vernon [7], Thomas Elias Cocolios [8], Kieran Flanagan [9], Ronald Fernando Garcia Ruiz [10], Sarina Geldhof [11], Dag Hanstorp [12], Sonja Kujanpää [13], Louis Lalanne [5], Gerda Neyens [14], Miranda Nichols [12], Jordan Reilly [9], Andrew J. Smith [2], Quanjun Wang [15], Shane Wilkins [16], Xiaofei Yang [17], Ruben de Groote [18], Bram van den Borne [5]

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The collinear resonance ionization spectroscopy (CRIS) experiment at the ISOLDE facility at CERN specializes in performing high-sensitivity laser spectroscopy on species with production rates as low as 101-102 nuclei per second. Recently, thanks to the ability of the technique to perform both high-resolution spectroscopy at high precision and low-resolution spectroscopy with a short experimental runtime, the CRIS experiment has expanded its activities to include laser-spectroscopic campaigns on radioactive molecules.

Following the first laser spectroscopy of radium monofluoride (RaF) [1], further CRIS campaigns on beams of short-lived radioactive molecules are being envisioned. Actinium monofluoride (AcF) has been identified as a promising candidate system for the first measurement of a nuclear Schiff moment across the nuclear chart [2], and a CRIS experiment to pin down the electronic structure of AcF for the first time has been planned for the Fall of 2022.

Additionally, to further improve the performance of the CRIS experiment, a voltage-scanning setup has been recently installed, to combine the techniques of frequency and voltage scanning. Commissioning tests with stable beams of Al and Ag have demonstrated that combining the two scanning approaches can accelerate the experimental runtime by a factor of 4 while ensuring that alterations in the ion trajectories are minimized. Additionally, a new laser-ablation ion source based on a radiofrequency ion guide within a gas cell is under construction, aiming to improve the ability of the CRIS experiment to optimize the selection of a laser scheme for atomic and molecular studies.

This contribution will present the recently implemented and planned upgrades at CRIS along with recent results.

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3 Oct
3:10pm

Atomic structure investigation of curium by laser mass spectroscopy

Nina Kneip[1], Felix Weber [2], Magdalen A. Kaja [2], Christoph E. Düllmann [3], Christoph Mokry [4], Sebastian Raeder [5], Jörg Runke [6], Dominik Studer [2], Norbert Trautmann [7], Klaus Wendt [2]

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As a transuranium element with proton number $Z = 96$, curium is considered as one of the "minor actinides" in spent nuclear fuel. It is produced during burn-up by a series of nuclear reactions from ^{238}U; spent nuclear fuel contains about 20 g/tonne. Nineteen curium isotopes from ^{233}Cm to ^{251}Cm are known [1], with some exhibiting long half-lives between a few days and 10^7 years. As these include strong α-emitters as well as fissionable isotopes with large fission cross section, it is considered for transmutation as a highly radiotoxic contaminant. Targeted production of curium isotopes is achieved by neutron-irradiation of plutonium isotopes in high flux research reactors. As a mid-range actinide element within the Periodic Table, Cm has an electronic odd-parity ground state configuration $5f^7 6d7s^2\,{}^9D^o_{2,3,4,5,6}$ and a second nearby located even-parity configuration $5f^8 7s^2\,{}^7F_{0,1,2,3,4,5,6}$. Accordingly, its atomic structure is very rich, highly complex and so far only known to some degree.

Resonance ionization mass spectroscopy (RIMS) at the RISIKO mass separator of Mainz University has been applied for off-line studies of the Cm atomic structure within a series of investigations on long-lived actinides [2,3]. Due to its high ionization efficiency and outstanding elemental selectivity the technique is an excellent tool for high precision optical spectroscopy of atoms, especially regarding minuscule and rare samples, for the selective production of ions of a given element and, finally, for selective and sensitive ultra-trace determination [4]. A sequence of carefully selected optical transitions is used as resonant laser excitation ladder up to ionization. The combination with high transmission mass separation permits for quantitative low background detection of individual ions within an isotopically pure ion beam [5]. The laser system and the layout of the laser ion source unit are the central aspects of RIMS and determine the quality and significance of the spectroscopic data [5,6,7]. In Cm, three first excitation steps from the $5f^7 6d7s^2\,{}^9D^o_2$ atomic ground state to the $5f^7 6d7s7p\,{}^9D_3$, $5f^8 6d7s\,{}^9D_3$, and $5f^7 6d7s7p\,{}^7D_2$ levels were studied for ^{248}Cm. Based on all these steps, Rydberg levels were identified and their convergences were analyzed to deliver a precise value of the first ionization potential (IP). The Rydberg analysis was complicated due to the high spectral line density and strong configuration interactions. The IP value was independently confirmed by involving the field ionization approach with varying external electric field and applying the saddle point model. An IP value of 48330.73(18) cm^{-1} was obtained from the weigthed mean of the results from both methods; which certifies a slight underestimation of the former literature IP value of 48324(2) cm^{1} by Köhler et al., measured in 1996 [8].

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Invited
3 Oct
4:00pm

Recent highlights from laser spectroscopy at COLLAPS-CERN

Liss Vazquez Rodriguez[1,2] on behalf of the COLLAPS collaboration

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High-resolution collinear laser spectroscopy has been recently performed on a long sequence of tin (Z=50) and lead (Z = 82) isotopes at COLLAPS/CERN. Hyperfine structures and isotope shifts have been measured and high-precision values of electromagnetic moments and charge radii of ground and isomeric states are extracted. Similar quadratic trends are observed for the quadrupole moments of the 11/2- and 13/2+ isomeric states in the semi-magic nuclei. The picture is not the same for the ground states where the pattern changes from linear, in tin, to quadratic, in lead. Differences in charge radii between the high-spin isomeric states and the nuclear ground states, on the other hand, also show a surprisingly similar behaviour. These regularities will be discussed in the framework of nuclear structure with emphasis on how, under certain conditions, simplicity arises out of complexity.

RAPTOR – a novel approach for high-resolution laser-resonance ionization spectroscopy of radioactive elements

3 Oct
4:30pm

Sonja Kujanpää[1], Michail Athanasakis-Kaklamanakis [2], Wouter Gins [1], de Groote Ruben [3], Iain Moore [1], Andrea Raggio [1], Mikael Reponen [1]

[1] *University of Jyväskylä*
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[3] *Ku Leuven*

The Resonance ionization spectroscopy And Purification Traps for Optimized spectroscopy (RAPTOR) project is a new experimental setup located at the Ion Guide Separator On-Line (IGISOL) laboratory in the Department of Physics of the University of Jyväskylä. RAPTOR combines the two most common methods for laser spectroscopy in use at radioactive ion beam facilities: collinear laser spectroscopy and in-source laser-resonance ionization spectroscopy, resulting in perhaps the most promising approach for optical spectroscopy by exploiting the high selectivity of resonance laser ionization, the high efficiency of ion detection, and the high resolution permitted using fast beams. This technique, collinear resonance ionization spectroscopy (CRIS) [1], was pioneered in the past decade at the Isotope Separator On-Line Device (ISOLDE) at the European Organization for Nuclear Research (CERN).

While the conventional collinear laser spectroscopy and CRIS methods exploit the kinematic compression of Doppler-broadening effects with beam energies of 30-60 keV, the RAPTOR device uniquely employs beam energies of only a few keV. Although the lower beam energy leads to somewhat lower spectral resolution, it allows for the improvement of the charge-exchange efficiency in the neutralization process, as the probability to neutralize into a specific atomic state increases when the beam energy decreases, also increasing the selectivity of the process. Measurements requiring high efficiency, for example the short-lived bismuth isotopes, are thus uniquely suitable for RAPTOR as the energy of the ions can be optimized to suit the optimum charge-exchange requirements and enables the study of many outstanding physics cases using exotic isotopes that are challenging to produce with traditional ISOL-type facilities.

My contribution will present the technical details and planned upgrades of the RAPTOR device. Recent results from ongoing commissioning tests, such like first RIS spectra from stable copper and ion beam transport simulations will also be presented.

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3 Oct
16:50pm

Looking for CP violation in nuclear beta decay: First data-taking of the MORA experiment at JYFL, Finland

Abhilasha SINGH[1]

[1] *GANIL*

The MORA project focuses on ion manipulation in traps and laser orientation methods for the searches for New Physics (NP) in nuclear beta decay, looking for possible hints to explain the matter-antimatter asymmetry observed in the Universe. The JYFL Accelerator Laboratory and more specifically the IGISOL facility provide an ideal environment for the initial phase of the MORA experiment. The precise measurement of the so-called triple D correlation is sensitive to Time reversal violation, and via the CPT theorem, to CP violation. The D correlation parameter is particularly sensitive to the existence of Leptoquarks, which are hypothetical gauge bosons appearing in the first theories of baryogenesis. Leptoquarks are now actively searched for at the LHC, the measurements from which provide competitive and complementary constraints. MORA will use an innovative in-trap laser polarization technique for the precision measurement of the D correlation in the beta decay of 23Mg.

In this regard, the first test experiment with a 23Mg beam has been carried out in the IGISOL facility in Feb 2022. For the initial offline optimization, 23Na+ ions slowed down to 100 eV from the RF cooler buncher could be efficiently tuned for trapping. For 500 ms trapping time, efficiencies of 5 to 50% were achieved. During the beam time, a significant amount of 23Mg could be produced; 105 ions per µA of the primary proton beam. A 90 mW circularly polarized laser beam could be injected and aligned in the trap. Despite these achievements, a large contamination of 23Na and a high RF noise on the recoil ion detectors hindered the recording of β-recoil coincidences.

The next experiment will be performed at the end of May 2022 addressing these issues. New target heads and ion guides have already been prepared to remove the sodium contamination and a new RF generator has been employed to suppress the unwanted high order harmonics. After reducing the contamination of 23Na, we should be able to assess the performance of the innovative in-trap laser polarization technique. Along with the whole description of the project, I will be discussing the proof-of-principle measurement and progresses of the MORA experiment.

2022. Oct. 4. (Tuesday)

Studies of the two-step scheme with a ^{132}Sn beam for next-generation RI-beam production method in the medium-heavy very-neutron-rich region

Invited
4 Oct
9:00am

Hiroshi Suzuki[1], Daniel Bazin[2], Naoki Fukuda[3], Walter, F. Henning[4], Nobuaki Imai[5], Naohito Inabe[1], Keita Kawata[6], Noritaka Kitamura[6], Tetsuro Komatsubara[1], Zeren Korkulu[7], Toshiyuki Kubo[1], Kensuke Kusaka[1], Shin'ichiro Michimasa[8], Jerry Nolen[9], Makoto Ohtake[1], Hiromi Sato[1], Yohei Shimizu[3], Toshiyuki Sumikama[3], Hiroyuki Takeda[3], Oleg Tarasov[2], Hideki Ueno[1], Yoshiyuki Yanagisawa[None], Koichi Yoshida[3], Deuk Soon AHN[10]

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[3] *RIKEN*
[4] *Argonne National Laboratory, Technische Universitaet Muenchen*
[5] *CNS, the University of Tokyo*
[6] *CNS, University of Tokyo*
[7] *IBS, CENS*
[8] *The University of Tokyo CNS*
[9] *Argonne National Laboratory*
[10] *Center for Exotic Nuclear Studies, IBS*

The usefulness of the two-step scheme with a ^{132}Sn beam was investigated [1], which was proposed for efficient production of medium-heavy very-neutron-rich radioactive isotopes (RI) [2] as an alternative method to the direct production by means of in-flight fission of a ^{238}U beam (one-step scheme). The system of the two-step scheme consists of an isotope-separation online (ISOL) system and an in-flight fragment separator. Long-lived neutron-rich RIs (e.g., ^{132}Sn) are produced by ISOL with a thick U target and a high-intensity proton beam in the first step, and more neutron-rich RI beams (e.g., ^{128}Pd) are produced by a projectile fragmentation from the re-accelerated less-exotic RI beams in the second step.

We measured production cross sections of very neutron-rich RIs around a $N = 82$ region beyond ^{125}Pd, up to which the cross sections had already been measured at GSI [3], with a 278-MeV/nucleon ^{132}Sn beam produced by the BigRIPS separator [4] impinging on a 5.97-mm Be target. The yields obtained by the two-step and one-step schemes were estimated based on the measured cross sections, and we examined whether and to what extent the two-step scheme at future 1-MW beam facilities can reach further into the neutron-rich regions. This comparison suggests that the two-step scheme with the ^{132}Sn beam provides yields >40-times higher than

those with the one-step scheme for the very neutron-rich $N = 82$ region. Moreover, by using various RI beams over the nuclear chart from ISOL, certain regions of very neutron-rich RIs around $N = 50$, 60, 82, and 90 regions, including the supernova r-process path, can be produced with greater yields than by the one-step approach.

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LISE^{++}_{cute}, the latest generation of the LISE^{++} package, to simulate rare isotope production with fragment-separators

4 Oct
9:30am

Oleg Tarasov[1], Bradley Sherrill [1], Daniel Bazin [1], Ksenia Tarasova [1], Marc Hausmann [1], Mauricio Portillo [1], Michelle Kuchera [2], Peter Ostroumov [1], Tong Zhang [1]

[1] *FRIB / MSU*
[2] *Davidson College*

The LISE^{++} software for fragment separator simulations has undergone a major update. The package, widely used at rare isotope beam facilities, can be used to predict intensities and purities of rare isotope beams and for planning and running of experiments using in-flight separators. It is especially useful for radioactive beam production as its results can be quickly compared to on-line data. The LISE^{++} package has been ported to the Qt-framework in order to support modern compilers and computing methods. The benefits include 64-bit operation and LISE^{++} availability on three different platforms: Windows, macOS and Linux. In addition, the porting provides the ability to take advantage of future computational improvements. The updated package is named LISE^{++}_{cute} to indicate a major step forward from the previous Borland-based versions. The LISE^{++}_{cute} package remains essentially identical for all platforms, keeping all previous versions functionality with implementation of new features and utilities. In addition to porting to the new platform, new features and modifications been added, such as 3-D Monte Carlo plotting including 3-D envelopes. The codes ETACHA4 and GEMINI++ were ported to a GUI and implemented in the package. In context of production models, new utilities have been developed such as a minimization procedure using the Abrasion-Ablation model to adjust its parameters based on experimental projectile-fragmentation cross-sections and an initial fissile nuclei analyzer.

The next steps in the LISE^{++}_{cute} package development will be discussed in this presentation. These include the creation of a LISE^{++}_{core} library that will allow integration of LISE^{++} calculations within control systems. This will directly assist in the tuning of fragment separators. Code parallelization will allow use of modern computing architecture and are essential to achieve faster computation.

4 Oct
9:50am

New developments for experiments at the three branches of the Fragment Separator FRS

Emma Haettner[1], Hans Geissel[2], Bernhard Franczak[1], Christoph Scheidenberger[3], Timo Dickel[4], Marco Durante[1], Zhuang Ge[1], Christoph Hessler[1], Christine Hornung[1], Daria Kostyleva[1], Sergey Litvinov[1], Katia Parodi[5], Wolfgang R. Plass[2], Rinku Prajapat[6], Sivaji Purushothaman[1], Petra Schuett[1], Yoshiki K. Tanaka[7], Helmut Weick[1], Jianwei Zhao[1] Super-FRS Experiment Collaboration, BARB Collaboration

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The FRagment Separator FRS at GSI features three branches for experiments with in-flight separated beams, the symmetric branch, the storage-ring branch connected to the Experimental Storage Ring and CRYRING complex (ESR/CRYRING), and the target hall branch to various caves, where experimental setups for Reaction experiments with Relativistic Radioactive Beams (R3B) and for Biomedical Applications of Radioactive ion Beams (BARB) are located. The symmetric branch is used mainly for spectrometer experiments and implantation experiments, where the nuclei of interest are completely slowed down and thermalized and then studied by decay- or mass-spectrometry. In order to study the most exotic nuclei, the rate of the nuclei of interest is often a critical parameter. For a significant rate increase, a high-transmission ion-optical mode and very thick production targets making use of two-step reactions have been developed and tested; results obtained with Pb and Xe fragment beams will be reported.

At the ESR, an energy-isochronous ion-optical mode has been available for direct mass measurements of very short-lived nuclei for more than two decades. With revolution-time measurements only, the high mass-over-charge accuracy and resolving power is limited to a narrow window in the magnetic rigidity. This statement has been proven first by using slits at the second focal plane of the FRS. Instead of an independent magnetic rigidity measurement, one can also measure the velocity with two TOF detectors as it is foreseen for the CR at FAIR and meanwhile implemented at the CSRe in Lanzhou. An equivalent way is to simultaneously measure the magnetic rigidity and the revolution frequency of each circulating stored ion. Calculations show that an upgraded position sensitive TOF detector, located at a dispersive position in the ESR lattice, will improve the accuracy and the mass resolution without limiting the intensity of the stored exotic nuclei.

The third branch of the FRS leads to the target hall with the medical cave as one possible destination. Recently a joint effort between the FRS and the biophysics groups of GSI was started to perform biomedical experiments relevant for hadron therapy with positron emitting carbon and oxygen beams. The ion-optics and diagnostics for this new branch have been prepared and pure positron emitting ^{15}O-ions were provided to the medical cave for the first time. An overall conversion efficiency of about 6×10^{-4} for ^{15}O fragments per primary ^{16}O projectile was reached.

Work partly supported by ERC AdG no. 883425 (BARB)

4 Oct
10:10am

Current Status of In-flight Fragment Separator for RAON

Do Gyun Kim[1], Chong Cheoul Yun [1], Hyun Man Jang [1], Eunhee Kim [1], Jang Youl Kim [1], Yong Hwan Kim [1], Sukjin Choi [1]

[1] *Institute for Basic Science*

The in-flight fragment (IF) separator of RAON, the main device for producing rare isotope (RI) beams for nuclear science research and applications, is under development. For the purpose of using not only in-flight fission of uranium beams but also projectile fragmentation reactions, the IF separator of RAON is designed to have angular acceptance and momentum resolution of ±40 mrad and ±3%, respectively. The IF separator mainly consists of a target, beam dump, magnets, and detector systems. The high-power target and beam dump, up to 80 kW, were fabricated using graphite. The off-line test of the target and beam dump has been completed and a heat loading test using induction heating is being prepared. The IF magnet system consists of a total of 8 dipole magnets, 15 sets of quadrupole magnet triplet, 2 sextupole magnets, and power supply systems. High field and large aperture quadrupole magnets are required to accommodate the high angular acceptance of the IF separator design, for which low and high temperature superconducting (LTS and HTS) magnets are used. In the high radiation region near the production target, warm iron HTS quadrupole magnets are used to reduce the cold mass and to remove large radiation heat loads effectively at the temperature of ~40K. In the other region, cold iron LTS quadrupole triplets are used. The production of the IF electromagnet has been completed, and the performance test of the LTS quadrupole magnet triplets is in progress. Also, detectors for particle identification (PID) and data acquisition (DAQ) systems are currently being installed at the focal planes of the IF separator. All the components of the IF separator will be installed by end of this year, and the integrated machine commissioning will be started in 2023. Details on the development status of the IF separator of RAON will be discussed in the presentation.

The WASA-FRS project at GSI and its perspective

Invited
4 Oct
11:00am

Takehiko Saito[1]

[1] *High Energy Nuclear Physics Laboratory, RIKEN*

Studies of sub-atomic bound systems with hyperons and an mesons can provide essential information on the fundamental baryonic interaction and the origin of the mass. They can be studied by employing energetic heavy ion beams and proton beams above 2 A GeV. For these studies, the precision for measuring ejectiles moving to the very forward directions and other associated particles from the reaction and decay of nuclei of interest emitted with a wider angular distribution is the key. We have developed a novel technique for these studies by employing the fragment separator FRS at GSI and the WASA detector, and the project employing this technology is so-called "the WASA-FRS project" [1]. The WASA detector with a superconducting solenoid magnet and other associated detectors is mounted at the mid-focal plane of the FRS, and light particles like mesons and protons are measured by the WASA detector. Heavier ejectiles like deuterons and helium isotopes were measured by the FRS behind the mid-focal plane with an excellent momentum resolving power. Experiments for studying light hypernuclei and eta'-nuclei were already performed in the first quarter of 2022. The details of the WASA-FRS project and its perspective will be discussed.

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4 Oct
11:30am

Ultraviolet Spectroscopy of the Actinium-229 beta decay: the first observation of the radiative decay of the 229Th low-energy isomer

Piet Van Duppen[1], Sandro Kraemer[2], Andre Vantomme [2], Arno Claessens [2], Goele Magchiels [2], Guilherme Correia [3], Hilde De Witte [2], Janni Moens [2], Kjeld Beeks [4], Lino Da Costa Pereira [2], Michail Athanasakis [3], Mustapha Laatiaoui [5], Niyusha Hosseini [4], Paul Van Den Bergh [2], Peter Thirolf [6], Premaditya Chhetri [2], Rafael Ferrer [2], Razvan Lica [3], Renan Villareal [2], S. M. Tunhuma [2], Sarina Geldhof [2], Sebastian Raeder [7], Silvia Bara [2], Simon Sels [2], Thorsten Schumm [4], Ulrich Wahl [8], Yuri Kudrayvtsev [2]

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[7] *GSI*
[8] *ULisboa*

A unique feature of thorium-229 is its isomeric first excited state with an exceptionally low excitation energy, proposed as a candidate for future nuclear optical clocks [1]. The small nuclear moments are expected to outperform the accuracy of current state-of-the-art atomic clocks by about an order of magnitude [2]. The current best values of the excitation energy are 8.28(17) eV and 8.10(17) eV[3,4]. These were determined using two different measurement techniques whereby the isomer is populated in the alpha decay of uranium-233. The development of an optical clock requires, however, knowledge of the excitation energy by at least an order of magnitude more precise. Spectroscopic experiments searching for a direct signature of the radiative decay have to-date been unsuccessful, partially due to the background induced in the preceding alpha decay.

An alternative approach using the beta decay of actinium-229 is studied as a novel method to populate the isomer with high efficiency and in low background conditions [5]. Produced online at the ISOLDE facility, actinium is laser-ionized and implanted into a large-bandgap crystal in specific lattice positions, suppressing the electron conversion decay channel of the isomer. A favourable feeding pattern is significantly increasing the population of the isomer compared to uranium-233 and the lower energy deposit of the beta compared to the alpha decay results in a significantly reduced luminescence background.

In this contribution, a dedicated setup for the implantation of a francium/radium/actinium-229 beam into large-bandgap crystals and the vacuum-ultraviolet spectroscopic study of the emitted photons will be presented. From the results obtained during a first measuring campaign using MgF_2 and CaF_2 crystals as host material it can be concluded that the radiative decay of the thorium-229 isomer has been observed for the first time, the excitation energy of the isomer has been determined with a factor of 5 improved uncertainty and the ionic lifetime in a crystalline environment was determined.

References

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[5] M. Verlinde et al., Physical Review C, 100, 024315 (2019)

Development of new ionization chamber specialized in high-Z beam

4 Oct
11:50am

Masahiro Yoshimoto[1], Naoki Fukuda[1], Riku Matsumura[2], Daiki Nishimura[3], Hideaki Otsu[1], Yohei Shimizu[1], Toshiyuki Sumikama[1], Hiroshi Suzuki[1], Hiroyuki Takahashi[3], Hiroyuki Takeda[1], Junki Tanaka[1], Koichi Yoshida[1]

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[2] *Saitama University*
[3] *Tokyo City University*

RI Beam Factory (RIBF) at RIKEN Nishina Center for Accelerator-Based Science provides various RI beams from 238U 345 MeV/u primary beam. Here we report the new experimental results on high-Z beam production. The ionization chamber (IC) for energy-loss measurement is an essential detector for deducing the atomic number (Z) in flight in the BigRIPS spectrometer to identify the particles. The conventional IC with a low-cost gas mixture of 90% argon and 10% methane does not provide sufficient Z resolution for high-Z beams, especially Z>80 region, around 200-250 MeV/u which is a typical energy at RIBF.

Because the high-Z beam is more likely to capture electrons in material than the low-Z beam, which mostly keeps fully stripped, the number of charge-state changes in the IC gas affects the energy-loss distribution. For example, He-like state of U beam at 200 MeV/u, which is the most abundant charge state in material, changes the charge state approximately four times in the IC with the argon-based gas mixture, which is not sufficient for the energy-loss measurements. To enhance the Z resolution of the high-Z particles, xenon gas with an larger cross section of the charge-state changing is promising. Approximately 70 times of the charge-state changes of U beam at 200 MeV/u in the IC with a gas mixture of 70% xenon and 30% methane are expected to narrow the width of the energy-loss distribution.

The Z resolution of the IC with the argon-based and xenon-based gas mixtures was measured at BigRIPS using cocktail beam in the Z=60-90 region with 200-240 MeV/u. The results show the xenon-based gas mixture dramatically improves the Z resolution for Z>70 particles compared with the argon-based gas mixture. Furthermore, the xenon gas was found to be effective for the Z identification in this energy region, since the same energy-loss is obtained for even different incident charge states. In conclusion, the xenon-based gas IC strongly promotes the beam delivery of the high-Z region with the clear particle identification from BigRIPS spectrometer.

VAMOS : Performances and Physics Opportunities

Invited
4 Oct
2:20pm

Diego Ramos[1]

[1] *GANIL/CEA-CNRS*

The Variable Mode Spectrometer (VAMOS) is a large acceptance magnetic spectrometer o at the Grand Accélérateur National d'Ions Lourds (GANIL), France, that allows to reconstruct charged-particle trajectories. The performances of the spectrometer allow to identify a large range of products in terms of mass, nuclear charge, ionic charge state and velocity vector from nuclear reactions. During the last years, different experimental campaigns were carried out using the VAMOS spectrometer both, in a single mode, such as the fission program in inverse kinematics, or coupled with additional detectors. Particularly remarkable was the coupled operation with the Advanced GAmma Tracking Array (AGATA) exploring physical cases covering nuclear structure and nuclear reactions studies. The highly-segmented silicon array (MUGAST) campaign offered the opportunity to study nuclear structure and astrophysics from direct reactions benefiting from exotic SPIRAL1 beams. Along with the different campaigns, the VAMOS spectrometer underwent continuous improvement in terms of detection and electronics that allowed to exploit its capacity reaching unprecedented results.

In this talk, I will presented an overview of the recent experimental campaigns that were carried out with the VAMOS spectrometer as well as the improvements of the setup that drove the spectrometer and the associated detectors to the current state.

4 Oct
2:50pm

Commissioning results of ISOL beam lines with ^{133}Cs and ^{120}Sn beams at Rare Isotope Science Project

Takashi Haashimoto[1], Hee-Joong Yim [1], Jae Hong Kim [1], Young-Ho Park [1], Seongjin Heo [1], Kyoung-Hun Yoo [1], Jinho Lee [1]

[1] *Institute for Basic Science, Rare Isotope Science Project*

Radioactive isotope (RI) beam techniques are expanding the playing field of nuclear physics, and new insight of nuclei are given by continuously experimental and theoretical efforts. Reaccelerated RI beams based on ISOL technique is informative for more precise measurements with high statistics, because these beams have both of excellent quality and high intensity. In addition, such RI beams are utilized to RI productions, the playing field can be expanded to more exotic region. Very low-energy RI beams extracted from ISOL are also convenient for not only nuclear physics but also material science and cancer therapy. For these purposes, we are developing a high power ISOL facility.

ISOL system at Rare Isotope Science Project (RISP) consists of a proton cyclotron, a target ion source (TIS), a pre-mass separator, a radio frequency quadrupole cooler buncher (RFQCB), an electron beam ion source (EBIS) charge breeder, and an A/q separator. Experimental Physics and Industrial Control System (EPICS) was adopted for the ISOL control system as a standard framework. Construction of the system and optical components alignment were completed on 2020, and now is commissioning with stable ion beams. Since we developed a surface ionization ion source and a Laser ion source, the commissioning combining all devices is performed by using ^{133}Cs, and ^{120}Sn beams from the TIS. As a result, we found the pre-mass separator beam line setting condition with required mass resolving power (¿ 400) and 100% beam transmission efficiency. Although the beam commissioning of the A/q separator is undergoing, the beam was able to transport from the TIS to the end of ISOL beam line, that is the entrance of RFQ accelerator system.

In this presentation, the beam commissioning results for the pre-mass separator and the A/q separator will be reported. In addition, future test plans and schedule will be discussed.

SECAR: A recoil separator for nuclear astrophysics

4 Oct
3:10pm

Fernando Montes[1], George Berg [2], Jeff Blackmon [3], Kelly Chipps [4], Manoel Couder [2], Uwe Greife [5], Hendrik Schatz [6], Smith Michael [4], Pelagia Tsintari [7], Sara Miskovich [8], Hood Ashley [6], Louis Wagner [9], Zach Meisel [10], Georgios Perdikakis [7], Ruchi Garg [6], Catherine Deibel [3], Caleb Marshall [11], Kiana Setoodehnia [6]

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[6] *FRIB*
[7] *Central Michigan University*
[8] *SLAC*
[9] *TRIUMF*
[10] *U. Ohio*
[11] *FRIB/Ohio*

The recoil mass separator, SECAR (SEparator for CApture Reactions), recently commissioned at the Facility for Rare Isotope Beams (FRIB), enables direct measurements of proton- and alpha-capture reaction rates on proton-rich nuclei. SECAR will take advantage of radioactive beams produced by FRIB via projectile fragmentation, which are then stopped, and reaccelerated to astrophysical energies at the ReA3 facility. After a reaction occurs by impinging the reaccelerated beam on a hydrogen or helium SECAR target in gaseous or solid form, the reaction recoils are counted at SECAR, where a sequence of magnets and Wien filters separate them from the unreacted beam. The preparation of the SECAR system for accommodating its first science measurements, including the development of alternative ion beam optics and a novel SECAR tuning technique using Machine Learning, along with preliminary results will be presented.

Invited
4 Oct
4:00pm

Commissioning of the Advanced Rare Isotope Separator ARIS at FRIB

Elaine Kwan[1], Kei Fukushima[1], Mauricio Portillo[1], Mallory Smith[1], Marc Hausmann[1], Mathias Steiner[1], Oleg Tarasov[1], Peter Ostroumov[1], Tong Zhang[1]

[1] *FRIB/MSU*

Commissioning of the in-flight separator system ARIS began in early 2022 at the Facility for Rare Isotope Beams (FRIB) at Michigan State University. The system consists of up to three stages of achromatic separation and can deliver beams to various experimental stations for nuclear and astrophysics studies, as well as other societal needs. In-flight products are generated with beams from a driver linac designed to deliver up to 400 kW of 200 MeV/u uranium ions on-target, and higher energies for lighter ions. The separator is nominally designed to transmit beams of phase space distribution widths up to 40 mrad and +/-5% for momentum. To enhance the transmission efficiency over various legacy beam lines, momentum compression can be imposed at the first degrader stage. Modes with no compression are also developed to avoid using a degrader in the preseparator. The first cycle of experiments began in March at about 1 kW of primary beam. Operation at higher power and beam energies has been progressing. A description of the system will be given along with results from commissioning and operational experience.

Funding Agency:
Work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661, the State of Michigan and Michigan State University.

Recent Progress of ISOL Facility at RISP

Invited
4 Oct
4:30pm

Jinho Lee[1], Taeksu Shin [1], Hee-Joong Yim [1], Young-Ho Park [1], Wonjoo Hwang [1], Jaehong Kim [1], Sung-Jong Park [1], Takashi Hashimoto [1], Dong-Joon Park [1], Seongjin Heo [1], Kyoung-Hun Yoo [2], Jae-Won Jeong [1], Byoung-Hwi Kang [1], Chaeyoung Lim [3], Junyoung Moon [1], Jongwon Kim [1], Young-Heum Yeon [1]

[1] *RISP*
[2] *UNIST*
[3] *Korea University*

The RAON heavy ion accelerator facility is currently in the stage of commissioning under the Rare Isotope Science Project (RISP) launched in 2011. The RAON is planned to utilize an advanced rare isotope beam produced with a high power target by the Isotope Separation On-Line (ISOL) facility, aiming to deliver high purity and intense, neutron-rich rare isotope beams to the post-accelerator and experimental facilities. The RAON ISOL facility consists of a target/ion source module surrounded by movable shielding blocks in a bunker, remote handling facilities for the target operation, a pre-mass separator, a RFQ cooler buncher, an EBIS charge breeder, and an A/q separator. Installation and alignment of the ISOL facility were completed in June 2021. The target/ion source module allows us to bombard a thick target with a 70 MeV proton beam of RAON, producing a variety of rare isotope beams. The produced isotope beams extracted from the target/ion source can be transported to a pre-mass separator at energies up to 60 keV, and will be cooled in a RFQCB. Cooled ion beams can be sent to two different experimental facilities, such as a Mass Measurement System and a Collinear Laser Spectroscopy in ISOL experimental hall. Alternatively, for post–acceleration of ion beams, the singly charged ion beam of interest can be bunched to 10^8 ions and then delivered to the EBIS charge breeder through the EBIS branch system. The preparation of multi charged ion beams for the post-acceleration using the superconducting linac of SCL3 will be carried out through the EBIS charge breeder and A/q separator to match the energy of 10 keV/u with A/q¡6 with the requirement of RAON Injector.

The first commissioning experiment of the ISOL system started from March 2021 using the ^{133}Cs and ^{120}Sn stable beams produced from the target container combined with the surface ion source and laser Ion source. The stable beam experiments have demonstrated the overall functioning of the RAON ISOL system, and we are planning to carry out the first RI beam test using the SiC target with 70 MeV proton of cyclotron at the end of 2022.

Invited
4 Oct
5:00pm

Development and Operation of High-Power Target Systems at TRIUMF

Alexander Gottberg[1]

[1] *TRIUMF*

With over five decades of experience in the production of accelerator-based secondary particles for science, TRIUMF ensures that Canada remains on the leading edge of supplying radioisotopes, neutrons, photons, and muons enabling fundamental science in the fields of nuclear, particle and astrophysics, as well as solid state and medical sciences and applications.

ISAC-TRIUMF is the only ISOL facility worldwide that routinely produces radioisotope beams from targets irradiated in the high-power regime in excess of 10 kW. TRIUMF's current flagship project ARIEL, Advanced Rare IsotopE Laboratory, will add two new target stations providing isotopes to the existing experimental stations in ISAC I and ISAC II at keV and MeV energies, respectively. In addition to the operating 500 MeV, 50 kW proton driver from TRIUMF's main cyclotron, ARIEL will make use of a 30 MeV, 100 kW electron beam from a newly in-house designed and build superconducting linear accelerator. Together with additional 200 m of radioisotope beamlines within the radioisotope distribution complex, this will put TRIUMF in the unprecedented capability of delivering three isotope beams to different experiments, while producing radioisotopes for medical applications simultaneously – enhancing the scientific output of the laboratory significantly.

The results of 20 years of operational experience and target and ion source developments at ISAC is being used to design and build the ARIEL target stations. These new designs are, in turn, applied to inform a fundamental ISAC target systems refurbishment campaign that addresses ageing infrastructure, as well as the raising demand for new beams, increased beam intensity and purity, facility uptime, radiation safety and operational efficiency.

The Super Separator Spectrometer (S^3) for the very high intensity beams of SPIRAL2

Invited
4 Oct
5:30pm

Herve Savajols[1] and the S3 collaboration[2]

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[2] *https://www.ganil-spiral2.eu/scientists/ganil-spiral-2-facilities/experimental-areas/s3*

The Super Separator Spectrometer S^3 [1] is, with the NFS (Neutrons For Science) facility, a major experimental system developed for SPIRAL2. It is designed for very low cross section experiments at low (¡15MeV/u) energy. It will receive the very high intensity (more than 1pµA) stable ion beams accelerated by the superconducting LINAG accelerator of SPIRAL2. S3 will be notably used for the study of rare nuclei produced by fusion evaporation reactions, such as superheavy elements and neutron-deficient isotopes. Such experiments require a high transmission of the products of interest but also a separation of these nuclei from unwanted species. Hence S^3 must have a large acceptance but also a high selection power including physical mass resolution. These properties are reached with the use of seven large aperture superconducting quadrupole triplets which include sextupolar and octupolar corrections in a two-stage separator (momentum achromat followed by a mass spectrometer) that can be coupled to the SIRIUS implantation-decay spectroscopy station [2] or to a gas cell with laser ionization to provide very pure beams for low energy experiments [3]. S^3 is now in the installation and tests phases. We will present the scientific objectives of GANIL-SPIRAL2 as well as the current status of the facility.

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

2022. Oct. 5. (Wednesday)

Target- and ion source development at CERN-ISOLDE

Invited
5 Oct
9:00am

Sebastian Rothe[1]

[1] *CERN*

At the CERN-ISOLDE radioactive ion beam facility, the thick targets are irradiated using a beam of 1.4 GeV-protons. One of ISOLDE's features is the large choice of ion source types and targets materials available on the menue, enabling us to select the optimial combination for optimal intensity and purity of the isotopes requested by the ISOLDE Users. Ever increasing demands in terms of isotope production yield, beam purity, and overall reliability of the employed systems are drivers of the continous development efforts.

Over the last years, CERN has invested especially in facilities and infrastructure that facilitate ongoing developments required for CERN-ISOLDE. A dedicated offline laboratory (Offline 2) has been recently equipped with a laser setup required for developments of specialized laser ion source types such as VADLIS and LIST. Moreover, it hosts a twin setup of the ISOLDE RFQ cooler and buncher (ISCOOL), which is envisaged to be used for studies of molecular beam creation and breakup as well as the development of the RFQ itself. For material development, especially for nano-structured materials, the new nano laboratory has just been commissioned and will enable to produce and develop nano actinide targets for ISOLDE.

In this contribution we shall describe the infrastructure required for target and ion source developments, highlight recent efforts and experimental results on both target material development and ion source development and we will give an outlook what to expect in the near future.

Invited
5 Oct
9:30am

Low Energy Radioactive Ion Beams at SPES for nuclear physics and medical applications

Alberto Andrighetto[1]

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Around the world, many facilities producing Radioactive Ion Beams (RIBs) using the Isotope Separation On Line (ISOL) technique have been or are under construction. Among others, SPES (Selective Production of Exotic Species) is the facility in the installation phase in these years in the Laboratori Nazionali di Legnaro (LNL). In this type of facility, the radioactive atoms are produced using a 40 MeV-200 μA proton beam impinging the Uranium Carbide (UCx) target composed by seven disks in order to dissipate the 8 kW beam power. The fission products, in the order of 10ˆ13 atoms/seconds, diffuse and effuse out of the target up to the ion source where are ionized and accelerated by an extraction voltage up to 40 kV. The formed RIB will be subsequently directed and focalized using different electromagnetic systems and purified in order to have a pure isotope beam without contaminants. The RIBs can be sent directly to the low energy experimental area and, afterwards, to the post-acceleration stage. Currently the installation program concerning the RIB source provides the set-up of the apparatus around the production bunker. The main objective is to provide in the next years, the first low-energy radioactive beams for beta decay experiments using the b-DS (beta Decay Station) set-up and for radiopharmaceutical applications by means of the IRIS (ISOLPHARM Radioactive Implantation Station) apparatus. The goal of the ISOLPHARM project is to provide a feasibility study for an innovative technology for the production of extremely high specific activity beta emitting radionuclides as radiopharmaceutical precursors.

In this presentation, all the specific issues related to the SPES RIB and the Low Energy beam lines will be appropriately presented and commented, showing the results obtained in the last years. The main RIB systems, such as ion source systems, target-handling devices and the installation of low energy transport line, will be presented in detail.

Developments for actinide molecular ion beams at CERN-ISOLDE

5 Oct
10:00am

Mia Au[1], Michail Athanasakis-Kaklamanakis [1], Jochen Ballof [2], Robert Berger [3], Katerina Chrysalidis [1], Paul Fischer [4], Sarina Geldhof [5], Reinhard Heinke [1], Jake Johnson [6], Ulli Köster [7], David Leimbach [8], Edgars Mamis [9], Bruce Marsh [1], Maxime Mougeot [1], Lukas Nies [1], Jordan Reilly [10], Moritz Schlaich [11], Christoph Schweiger [12], Simon Stegemann [1], Julius Wessolek [13], Frank Wienholtz [14], Shane Wilkins [15], Wiktoria Wojtaczka [16], Christoph E. Düllmann [17], Sebastian Rothe [1]

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[14] *TU Darmstadt*
[15] *Massachusetts Institute of Technology*
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The ISOLDE facility at CERN provides experiments with a wide range of isotopes across the nuclear chart, produced in reactions from 1.4 GeV protons with thick targets. The reaction products are typically delivered in the form of charged atomic ions, but molecular species can also be extracted. The development of molecular beams is motivated by improvements to beam extraction and purity as well as interest in studying the radioactive molecules themselves.

Molecules have been studied as a method to efficiently deliver beams of release-limited elements by forming and extracting volatile molecules [1,2] of otherwise refractory species such as carbon [3], boron [4] or refractory metals [5]. Additionally, delivering isotopes on a molecular sideband shifts the mass of interest, and can therefore be used as a technique to improve beam purity by changing the isobaric contamination situation. Beyond their use for enhanced extraction, molecules provide additional opportunities to search for fundamental symmetry violations and contribute to the development of new physics beyond the standard model [6,7]. Recent studies of radium fluoride at ISOLDE [8] demonstrate the experimental capabilities to study beams of radioactive molecules produced at radioactive ion beam facilities and further motivate the development of radioactive molecules.

We will present the first results of ongoing work on molecular ion beams of heavy elements at ISOLDE. Uranium carbide targets were used to produce molecular beams via injection of reactive tetrafluoro methane (CF_4) gas. The ion beam composition was studied using: the ISOLTRAP Multi-Reflection Time-of-Flight Mass Spectrometer (MR-ToF MS) [9] for identification by ToF mass measurements, online γ-ray spectroscopy at the ISOLDE tape station [10,11], and off-line α- and γ-ray spectrometry of ion-implanted samples. The results contribute to beam developments for actinide elements and radioactive molecules for fundamental physics research.

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Radioactive ion beam production yields using 1.4- and 1.7-GeV protons at CERN-ISOLDE

5 Oct
10:20am

Simon Stegemann[1], Alexandre Dorsival [1], Ana-Paula Bernardes [1], Bruce Marsh [1], Charlotte Duchemin, Cyril Bernerd [2], Edgar Reis [1], Edouard Grenier-Boley [1], Elodie Aubert [1], Erwin Siesling [1], Fabio Pozzi [1], Francesc Salvat Pujol [1], Francesco Cerutti [1], Gian Piero Di Giovanni [1], Giuseppe Lerner [1], Joachim Vollaire [1], Jose Alberto Rodriguez [1], Jose maria Martin Ruiz [1], Jose-Luis Sanchez Alvarez [1], João Pedro Ramos [3], Karl Johnston [1], Katerina Chrysalidis [1], Marco Calviani [1], Matthew Fraser [1], Maximilian Schuett [1], Mia Au [1], Piotr Krzysztof Skowronski [1], Ralf Erik Rossel [1], Reinhard Heinke [1], Sean Freeman [1], Sebastian Rothe [1], Simone Gilardoni [1], Thierry Stora [1], Thomas Elias Cocolios [4], Ulli Köster [5], Zoé Favier [1]

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CERN-ISOLDE is among the world-leading isotope separation on-line (ISOL) facilities providing radioactive-ion beams (RIBs) for research. ISOLDE's versatility is driven by a 1.4-GeV proton beam delivered by the Proton Synchrotron Booster and its target and ion source repertoire. While more than 1000 isotopes from 76 different elements have been produced at CERN-ISOLDE, user interest often focuses on exotic RIBs that are challenging due to low production and/or low release efficiency from the target-ion source system. As a result, target and ion source developments and facility upgrades for higher quality beams at CERN-ISOLDE are needed to increase the facility's capability. Experimental data shows that by increasing the proton energy, gains in production can be achieved in several regions of the nuclear chart. To validate the expected gain of such an upgrade, a campaign to measure and compare RIB yields using 1.4- and 1.7-GeV protons was recently launched at CERN-ISOLDE. In this contribution we will present the status of this campaign, highlight first experimental results and compare them to theoretical predictions.

Invited
5 Oct
11:10am

Bρ-defined isochronous mass spectrometry: a new tool for precision mass measurements of short-lived nuclei

Meng WANG[1] on behalf of the CSR-IMS collaboration

[1] *Institute of Modern Physics, Chinese Academy of Sciences, China*

Nuclear mass spectrometry is an intensively developing field in modern experimental physics. Among all the state-of-the-art methods, isochronous mass spectrometry (IMS) at storage rings plays an important role in broadband mass measurements of short-lived nuclei. However, high mass resolving power can be achieved only in a limited m/q-range with good isochronicity with the conventional IMS. To improve the situation, we have developed a brand new technique, the B-defined IMS, at the cooler storage ring CSRe in Lanzhou, and used it in mass measurements of neutron-deficient, fp-shell nuclides produced by the fragmentation of a ^{58}Ni beam. Using the simultaneously determined revolution times and velocities of the stored ions, the relation between ions' magnetic rigidities and orbit lengths is established, allowing to determine the magnetic rigidity of any stored ion according to its orbit length. Consequently, m/q values of the unknown-mass nuclides are determined. High mass resolving power has been achieved covering a large m/q-range over the full B-acceptance of the storage ring, starting a new era of the IMS. The masses of a series of nuclides are determined with high precision in one single setting. Among them, masses of ^{46}Cr, ^{50}Fe, ^{54}Ni are determined with relative uncertainties of (5 6)$\times 10^{-8}$, providing important input data for weak interaction physics.

Applying Heavy-Ion Storage Rings for Precision Experiments at the Intersection of Atomic, Nuclear and Astro-Physics

5 Oct
11:40am

Yury Litvinov[1]

[1] *GSI Helmholtz Center*

The storage of freshly produced radioactive particles in a storage ring is a straightforward way to achieve the most efficient use of such rare species as it allows for using the same rare ion multiple times. Employing storage rings for precision physics experiments with highly-charged ions (HCI) at the intersection of atomic, nuclear, plasma and astrophysics is a rapidly developing field of research.

There ae presently three accelerator laboratories, GSI Helmholtz Center Germany (GSI), Institute of Modern Physics in China (IMP), and Nishina Research Center in Japan (RIKEN) operating heavy-ion storage rings coupled to radioactive-ion production facilities. The experimental storage ring ESR at GSI, the experimental cooler-storage ring CSRe at IMP, and the Rare RI ring R3 at RIKEN offer beams at energies of several hundred A MeV. The ESR is capable to slow down ion beams to as low as 4 A MeV (beta=0.1). Beam manipulations like deceleration, bunching, accumulation, and especially the efficient beam cooling as well as the sophisticated experimental equipment make rings versatile instruments. The number of physics cases is enormous. The focus here will be on the most recent highlight results achieved within FAIR-Phase 0 research program at the ESR.

First, the measurement of the bound-state beta decay of fully-ionized 205Tl was proposed about 35 years ago and was finally accomplished in 2020. Here, the ESR is presently the only instrument enabling precision studies of decays of HCIs. Such decays reflect atom-nucleus interactions and are relevant for atomic physics and nuclear structure as well as for nucleosynthesis in stellar objects.

Second, the efficient deceleration of beams to low energies enabled studies of proton-induced reactions in the vicinity of the Gamow window of the p-process nucleosynthesis. Proton capture reaction on short-lived 118Te was attempted in 2020 in the ESR. Here, the well-known atomic charge exchange cross-sections are used to constrain poorly known nuclear reaction rates.

The performed experiments will be put in the context of the present research programs at GSI/FAIR and in a broader, worldwide context, where, thanks to fascinating results obtained at the presently operating storage rings, a number of new exciting projects is planned. Experimental opportunities are being now dramatically enhanced through construction of dedicated low-energy storage rings, which enable stored and cooled secondary HCIs in previously inaccessible low-energy range. The first such facility, CRYRING, has just been utilized for precision experiments at GSI with decelerated beams of HCIs transferred from the ESR.

Thanks to the fascinating results obtained at the ESR, the CSRe and the R3 as well as to versatile experimental opportunities, there is now an increased attention to the research with ion-storage rings worldwide. Dedicated ring facilities are proposed for ISOLDE at CERN, TRIUMF, LANL, and JINR.

5 Oct
12:00pm

A Brief Overview and Status of RAON

Taeksu Shin[1] on behalf of RISP

[1] *Institute for Basic Science*

RAON is the flagship rare isotope accelerator and science facility in Korea. After the blessing of the Korean government announcement for the construction of a rare isotope accelerator in 2009, the construction of RAON was launched in 2011 by the Rare Isotope Science Project (RISP) under Institute for Basic Science (IBS) to aim for a large scale basic science research facility.

RAON was designed to produce a variety of stable and rare isotope beams to be used for research in basic science and various applications. RAON consists of a heavy ion superconducting linear accelerator (linac) as the driver of IF(In-flight Fragmentation) system and a proton cyclotron as the driver for the ISOL (Isotope Separation On-Line) system and superconducting post-accelerator for the ISOL system. The ISOL and IF systems can be operated independently. In addition, the rare isotopes produced by the ISOL system can be injected into the superconducting linac for further acceleration to higher energies to produce even more exotic rare isotopes. This combined scheme of the ISOL and IF may be referred to as ISOLIF.

The construction of buildings and supporting facilities on a once green field is finished. Developments of major instruments for superconducting linear accelerators, cryo-plant systems, ISOL facility with Cyclotron, experimental facilities, and the post-accelerator superconducting linear accelerator (SCL3) are mostly done. The superconducting post-linac is under commissioning. ISOL facility uses a 70 MeV proton cyclotron, and low-energy experimental facilities such as KoBRA (Korea Broad acceptance Recoil Spectrometer and Apparatus) are also under commissioning. Here, we report on the overview and current status of the facilities.

2022. Oct. 6. (Thursday)

Ion catchers for short-lived isotope research: Challenges, concepts and applications

Invited
6 Oct
9:00am

Timo Dickel[1]

[1] *GSI*

Ion Catchers are gas-filled chambers to thermalize fast ion beams and convert them into low-energy beams. The origin of this is the IGISOL facility in Jyväskylä, Finland. There, the method of thermalizing short-lived nuclides in helium gas was pioneered more than three decades ago. Large volume Ion Catchers are today operated at many exotic ion beam facilities worldwide. They are used to thermalize exotic nuclides produced in fusion, in-flight fragmentation and fission, spontaneous fission, and multi-nucleon transfer reactions. The method is appealing as it is universal and applies to refractory elements. After the thermalization in the high-density buffer gas, typically helium, the ions are extracted and separated from the gas to form a "cold," low-energy beam of short-lived nuclides. This beam is further prepared (e.g., mass selection, dissociation of molecules) before it is delivered to high-precision experiments, such as mass spectrometry, mass-assisted decay, and collinear laser spectroscopy. Ion Catchers are also used for cooling exotic nuclides before re-acceleration to Coulomb barrier energy for reaction studies. Each application or production method has its specific needs and challenges. Still, it is typically the quest to maximize the rate capabilities and stopping efficiency while having extraction times well below 50 ms to access the most short-lived nuclides and isomers. The presentation will give an overview of the state-of-the-art concepts developed to meet these challenges, recent highlights and achievements, and future perspectives.

Invited
6 Oct
9:30am

Gas stopping techniques with reacceleration

Antonio C.C. Villari[1]
[1] *FRIB*

Gas stopping of rare isotope beams together with reacceleration is unique at the Facility for Rare Isotope Beams (FRIB) at the Michigan State University. The stopping techniques, with beam manipulation at very low energies, are important developments aimed to slow down fast beams for either use in stopped beam experimental devices or to be injected in the reaccelerator for experiments at energies from 0.3 MeV/u to 12 MeV/u depending on the Q/A of the ion. We developed innovative stopped beam systems that were designed to optimize the stopping and extraction efficiencies for various atomic number ranges, as well as to reduce contamination and increase extraction speed. Moreover, reacceleration of those beams involve techniques of cooling, bunching, charge breeding and acceleration by a state-of-the-art superconducting LINAC (ReA). In this contribution I'll show the latest results of various gas stoppers and techniques to eliminate contaminants after reacceleration by the ReA. Typical efficiencies of each step will be presented as well as plans for future developments.

This material is based upon work supported by NSF under grant PHY15-65546, and DOE-SC under award number DE-SC0000661

Development of the new helium gas catcher and nuclear mass measurements with the new MRTOF-MS behind the ZeroDegree spectrometer at RIKEN BigRIPS

6 Oct
10:00am

Aiko Takamine[1], Marco Rosenbush [2], Michiharu Wada [2], Shun Iimura [3], Wenduo Xian [4], Sidong Chen [4], Jinn Ming Yap [4], Hironobu Ishiyama [1], Peter Schury [5], Shunji Nishimura [1], Toshitaka Niwase [2], Sota Kimura [1], Yoshikazu Hirayama [2], Yuta Ito [6], Takao Kojima [1], Jenny Lee [4], Jiajian Liu [4], Shin'ichiro Michimasa [7], Hiroari Miyatake [8], Jun-young Moon [9], Momo Mukai [1], Sarah Naimi [1], Tetsu Sonoda [1], Hideki Ueno [1], Phong Vi [1], Yutaka Watanabe [5], Shuxiong Yan [10], Tik Tsun Yeung [11]

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A new helium gas catcher has been developed at the SLOWRI facility at RIKEN/RIBF aiming at the efficient conversion of the high-energy exotic RI beams from the BigRIPS separator to slow RI beams. The RI beams of relativistic energies are caught and thermalized in a cryogenic helium-gas filled chamber, and the thermalized ions are extracted by an RF ion guide system. The gas catcher has been combined with a multi-reflection time-of-flight mass spectrograph (MRTOF-MS), where atomic masses transported from the gas catcher can be measured with a precision of dm/m $< 10^{-7}$ [1,2].

The gas catcher consists of a two-stage RF carpet (RFCs), where the 1st stage adopts the RF-DC method [3] while the 2nd stage employs the "ion-surfing" method [4]. Initial offline transport tests have been performed using ions from surface ionizers (like Cs and K) by measuring ion currents with Faraday cups. After the gas catcher was combined with the MRTOF-MS apparatus and mass-selective ion counting was enabled, we moved to offline tests using stable ions produced in the He gas by the alpha-ray radiation and radioactive fission products from a ^{248}Cm source. Using the two different ways of testing, a reasonable performance of the gas catcher for upcoming online experiments was confirmed.

The first online commissioning run was conducted in the end of 2020 downstream of the ZeroDegree spectrometer using parasitic beams from in-beam gamma-ray experiments by the HiCARI campaign. We successfully measured more than 70 atomic masses during the commissioning. A new optimization has been implemented in 2021, which resulted in mass spectra with a mass resolving power on the order of 106 within a total time-of-flight of only 12.5 ms. We further expand the scope of our operations including decay correlated mass spectroscopy and efficient background reduction by in-MRTOF mass selection.

The status of our gas catcher development, a further improvement, new mass measurement results, and the capabilities of our setup will be discussed in this contribution.

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Multi-reflection time-of-flight mass spectroscopy of superheavy nuclides

Invited
6 Oct
11:00am

Aiko Takamine[1], D. Kaji[2], Hiromitsu Haba[3], Michiharu Wada[4], Peter Schury[4], H. Koura[5], H. Wollnik[6], Hiroari Miyatake[7], Hironobu Ishiyama[8], K. Morimoto[2], Marco Rosenbusch[9], Sota Kimura[8], Toshitaka Niwase[4], Yoshikazu Hirayama[4], Yuta Ito[10], Yutaka Watanabe[11], pierre brionnet[12]

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[12] *Super heavy team, NISHINA Center, RIKEN*

The KEK Wako Nuclear Science Center operates the KEK Isotope Separation System (KISS) which utilizes a small gas stopping cell to produce low-energy beams of multi-nucleon transfer (MNT) products. The group also co-manages, with the RIKEN SLOWRI Team, gas cells and multi-reflection time-of-flight mass spectrographs (MRTOF) at both the end of the ZeroDegree line of BigRIPS and following the GARIS-II recoil separator; a new system is presently under construction for use with the GARIS-III recoil separator. At KISS and the GARIS facilities, one of the primary interests are transuranium nuclides. For understanding both the general physics of superheavy nuclides and the role that fission-recycling of transuranium nuclides has on the astrophysical r-process, measurements of the masses and half-lives of these nuclides would be invaluable. To perform such measurements, which often involve extremely low production yields, we have been developing ion detectors for use with multi-reflection time-of-flight mass spectrographs which allow for ToF-decay correlated measurements. In the case of beta-decay, this technique can suppress signals from stable molecular ions while for alpha-decay it can provide a clear identification of radioactive ions. Both decays allow for the simultaneous determination of atomic mass and decay half-life in a single measurement. The future addition of a capability to measure x-rays and gamma rays will further expand our ability to probe these most exotic of nuclei.

Recent results and future plans for these devices will be presented.

6 Oct
11:30am

Uncovering the Proton Drip-Line of Tm with TITAN's MR-TOF Mass Spectrometer

Brian Kootte[1], Kilian Dietrich , Jens Dilling [2], Eleanor Dunling [3], Gerald Gwinner [4], Zachary Hockenbery , Chris Izzo [5], Andrew Jacobs [6], Abhilash Javaji , Yang Lan , Erich Leistenschneider [7], Eleni Marina Lykiardopoulou [6], Ish Mukul , Tobias Murboeck [8], Stefan Paul [9], Moritz Pascal Reiter [10], Jon Ringuette [3], Roshani Silwal [11], Rane Simpson , Ryohei Weil , A.A. Kwiatkowski [12]

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The change in nuclear binding energy associated with a nuclear decay or reaction can be determined directly using nuclear mass measurements. Precision mass spectrometry techniques, such as the Multiple-Reflection Time-of-Flight technique (MRTOF), are therefore indispensable tools for characterizing the strength of nuclear binding.

In the vicinity of the neutron-deficient limits of the N=82 shell closure, nuclear half-lives are sufficiently long to allow for high-precision mass measurements up to, and even across the proton drip-line. This provides a testbed for theoretical predictions of its location. Radioactive beam experiments were performed to establish the precise location of the proton drip-line in the Tm isotopic chain. This was achieved by obtaining previously unmeasued Tm masses, as well as by updating an anomalous mass contained within the 2020 Atomic Mass Evaluation.

These measurements utilized beams of radioactive isotopes produced at TRIUMF's Isotope Separator And Accelerator (ISAC), a well-established ISOL facility. ISAC delivered high-intensity beams to the MRTOF at TRIUMF's Ion Trap for Atomic and Nuclear Science (TITAN), where they were measured to precisions on the order of $\frac{\delta m}{m} \approx 10^{-7}$. Measurements of the rarest species were made possible by employing the recently implemented isobaric retrapping technique within the MRTOF to suppress contaminant species in the radioactive beam.

Development of neutron detection systems at the NDPS of RAON

6 Oct
11:50am

Kwang Bok Lee[1], Cheolmin Ham [1], Kyongho Tshoo [1], Seung-Woo Hong [2], Dal-Ho Moon [2], Sangjin Lee [1], Seong Jae Pyeun [1], Charles Akers [1], Minsik Kwag [1], Mi Jung Kim [1], Jae Cheon Kim [1], Taeksu Shin [1]

[1] *RISP*

[2] *Sungkyunkwan University*

Nuclear Data Production System (NDPS) at RAON has been built to produce nuclear data mainly generated by the reactions induced by neutrons of tens of MeV. For the neutron Time-Of-Flight (TOF) measurement, neutron monitoring detectors based on a gas-filled Parallel Plate Avalanche Counter (PPAC) and a MICRO-MEsh-GASeous (MICROMEGAS) detector have been developed by the Rare Isotope Science Project (RISP) and Sungkyunkwan University (SKKU). These detectors have a neutron converter with a thin ^{232}Th layer, which produces fission products due to fast neutrons. The PPAC achieved a 1 ns FWHM time resolution in a test with a ^{241}Am α source and also showed good performance when tested with fast neutrons generated by a 45 MeV proton beam through the ^{9}Be(p, n)^{9}B reaction. Additionally, EJ-301 liquid scintillation detectors will be used for the measurement of neutron flux with pulse shape discrimination capability. Slow charge signals as well as fast timing signals from the detectors will be processed for particle identification by a data acquisition(DAQ) system, located at a separate control room through 30 m long cables. Development of the detection system and the test results will be reported with on-site assembly status.

6 Oct
12:10pm

Status of LAMPS at RAON

Byungsik Hong[1]
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A new radioactive ion-beam accelerator facility, RAON, is under construction in Korea. Among the various experimental systems, the Large Acceptance Multi-Purpose Spectrometer (LAMPS) will be available in the high-energy experimental hall at RAON. The main goal of the LAMPS system is to investigate the nuclear equation of state (EoS) and, especially, the symmetry energy (SE) of the compressed nuclear matter, which should be essential to understand the effective nuclear interactions and structure of the astrophysical objects like neutron stars.
In this presentation, the status of the development and construction of the basic version of the LAMPS system will be presented. The components of the basic LAMPS system consist of the beam diagnostic elements, such as the Starting Counters (SC) and Beam Drift Chambers (BDC), the Time-Projection Chamber (TPC), the Barrel and Forward Time-of-Flight system (BTOF and FTOF), the forward neutron detector array (NDA), and the superconducting solenoid magnet. The overview of the present status for each detector components will be given with some prospects.

OEDO-SHARAQ system: multifaceted performances in low-energy RI production and high-resolution spectroscopy

Invited
6 Oct
2:00pm

Shin'ichiro Michimasa[1]

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The OEDO-SHARAQ system is the world's first beamline characterized by the energy-degrading of RI beams. While this system also has high performance on high-resolution nuclear spectroscopy with RI beams. A minor update of the system, performed in 2021, provided multifaceted improvements to the system in both effective energy-degrading and high-resolution spectroscopy with RI beams.

We report the achievements of OEDO-SHARAQ system in experimental studies implemented recently and introduce perspectives about upcoming physics programs of OEDO-SHARAQ.

Invited
6 Oct
2:30pm

A multi-purpose experimental instrument KoBRA for low-energy nuclear physics at RAON

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A multi-purpose experimental instrument, named as KoBRA (Korea Broad acceptance Recoil spectrometer and Apparatus), has been constructed for low-energy nuclear physics experiments at RAON (Rare Isotope Accelerator complex for ON-line experiments) in Korea. KoBRA will be utilized to produce rare isotope beams at an energy range of about 5 - 20 MeV/nucleon in early-phase experiments. A test was performed to measure the positions of 4He ions at the dispersive and achromatic focuses of KoBRA, using an 241Am α-source placed at the production target position. The position distributions of 4He ions are nearly consistent with the results of Monte Carlo calculation. The detailed design including ion optics and present status of KoBRA are described, together with the status of detectors for beam diagnostics and particle identification of rare isotopes.

Commissioning of the DESIR High-Resolution mass Separator

6 Oct
2:50pm

Julien Michaud[1], Laurent Serani [2], Arthur Balana [3], Phillipe Alfaurt [3], Bertram Blank [3], Laurent Daudin [3], Teresa Kurtukian Nieto [3], Benoit Lachacinski [3], François Méot [4], Franck Varenne [5]

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[4] *BNL*
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DESIR is the low-energy part of the SPIRAL2 ISOL facility in the final design at GANIL. The High-Resolution mass Separator (HRS) included in DESIR is a 180○ symmetric online separator with two 90○ magnetic dipole sections arranged with electrostatic quadrupoles, sextupoles and a multipole on the mid plane. The HRS is now completely mounted at LP2IB/CENBG and under commissioning for the next years before its transfer at the entrance of the DESIR facility. Optical aberrations, mainly introduced by the dipoles, must be corrected up to the highest order to guarantee an optimal resolution of the separator. They are measured with a pepperpot-type emittance-meter, analysed then corrected with the 48-poles electrostatic multipole. Up to now, 2nd order (hexapolar) and part of 3rd order (octupolar) aberrations are under control and an optimal FWHM separation has been achieved for two beams with $\Delta E/E = \Delta M/M = 1/25000$. We will present the effects of optical aberrations on the beam and its emittance figure, as well as the effect of the associated corrections with the multipole. Finally, we will show the latest resolution measurements and associated methodology.

6 Oct
3:50pm

The PUMA experiment at CERN

Frank Wienholtz[1]
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The main goal of the PUMA (antiProton Unstable Matter Annihilation) experiment is to use antiprotons as a tool to investigate properties of exotic nuclei. For this, antiprotons produced at the AD/CERN and decelerated by the ELENA storage ring will be captured, cooled and transported to the ISODLE facility where the antiprotons will be mixed with short lived isotopes. During this process, an antiproton can be captured by the nucleus and will subsequently annihilate with a neutron or a proton at the surface of the nucleus itself. The fingerprint of this annihilation will be measured using a time-projection-chamber. With this knowledge of the ratio of protons to neutrons on the outermost part of the nuclei distribution, phenomena like a neutron or a proton halo or neutron or proton skins can be investigated.

This contribution will give an overview of the PUMA experiment, present its status and highlight some of the main physics goals

Nuclear physics with TriSol at Notre Dame's Nuclear Science Laboratory

6 Oct
4:10pm

Tan Ahn[1], Chevelle Boomershine [1], Daniel Bardayan [1], Fabio Rivero [1], James Kolata [1], Maxime Brodeur [1], Patrick O'Malley [1], Regan Zite [1], Sam Porter [1], Scott Carmichael [1], Sydney Coil [1]

[1] *University of Notre Dame*

The detailed study of radioactive nuclei has resulted in opportunities for addressing many open questions in nuclear structure and nuclear astrophysics. For over three decades, the TwinSol separator at the University of Notre Dame has produced high-quality in-flight radioactive beams at low-energy for light isotopes that have been used in experiments aimed at nuclear structure, astrophysics, and fundamental symmetries studies. We have recently upgraded the TwinSol separator by adding additional elements: a dipole magnet, and a third solenoid. This new TriSol separator will improve the quality and purity of future radioactive beams. This improvement will enable the use of heavier beams and address beam contamination that has hindered past experiments. The current status of TriSol and its science program will be presented along with the role the TriSol program plays in the current landscape of nuclear physics user facilities. The TriSol program includes plans for the study of ^{11}C(p,p)^{11}C reactions for investigating the nature of the first stars, ^{14}O(α,p)^{17}F and its influence on reaction networks in x-ray bursts, the measurement of fusion reactions on Ne isotopes, and precision half-life measurements for fundamental symmetries studies.

6 Oct
4:30pm

Large-acceptance isotope identification array FAZIA: Status and R&D activities for upgrade

MinJung Kweon[1]

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The FAZIA apparatus is a multi-detector array designed to identify a wide range of charge and mass of reaction products in heavy-ion collisions in the Fermi energy domain. The basic module of FAZIA is the block, consisting of 16 three-layer telescopes. The first two layers are highly homogeneously doped Si detectors with the thickness of 300 μm and 500 μm, respectively, and the third layer is a 10 cm thick CsI(Tl) scintillator read out by a photodiode. The detector signals are extracted in real-time based on the digital signal processing implemented on the FPGAs. The recent experiments demonstrated that the charge could be discriminated up to more than Z=54 using the ΔE-E technique and the pulse shape analysis. In addition, the isotopic discrimination has been achieved up to Z ˜ 25 with the ΔE-E technique and up to Z ˜ 20 with the pulse shape analysis in the silicon layer. Recently, there have been activities for the FAZIA detector upgrade to use thicker and thinner silicon layers for enlarging the kinematic coverage. In addition, the R&D is in progress to make the front-end electronics board more compact and versatile. In this talk, we present the current status of the FAZIA detector and some highlights of the R&D activities for the upgrade.

Little-known ways to apply nuclear physics techniques to chemistry and medicine

Invited
6 Oct
4:50pm

Monika Stachura[1]

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As humans, we are a mixture of diverse chemical elements, a fragile composition that hangs in an improbable yet finely tuned balance. If this is disturbed, either due to a deficiency or excess of certain elements, it can lead to pathologies which have been linked to severe diseases such as cancer, Alzheimer's disease, or Parkinson's disease. For many metals in our body, such as Mg, Zn and Cu, the absence of convenient physical and spectroscopic properties with which to study them has held back a detailed understanding of their role in health and disease. Nuclear magnetic resonance (NMR) spectroscopy is a powerful technique for studying the structure and dynamics of metal-binding biomolecules in solution. In practice, however, NMR suffers from poor sensitivity for several elements. Beta-radiation detected NMR (β-NMR) spectroscopy is a lesser-known analogue of NMR which requires radioactive isotopes rather than stable ones, offers a billion-fold is based on the detection of beta-particles emitted anisotropically by spin polarized nuclei. The combination of nuclear spin polarization and high detection efficiency of beta-particles gives rise to a billion-fold or higher increase in sensitivity, and it allows for interrogation of elements which are otherwise difficult to access. In this presentation, I will demonstrate the potential of the β-NMR technique and highlight recent β-NMR experiments with biomolecules in solutions.

6 Oct
5:20pm

Optimal reaction energy for synthesis of element 119 via 51V+248Cm reaction probed by quasielastic barrier distribution measurement

Masaomi Tanaka[1]

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The periodic table is now completely filled up to the seventh period. The synthesis of elements 119 and 120 has been attempted in several cases using the combination of actinide targets and projectile beams heavier than ^{48}Ca. However, these new elements have not been discovered yet so far [1-4].

In the synthesis of superheavy elements, the reaction energy is the most important parameter that significantly affects the experimental efficiency. At RIKEN, element 119 is being searched using a ^{51}V+^{248}Cm hot fusion reaction. The optimal reaction energy of this reaction system is unknown since theoretical predictions vary widely. Under these circumstances, our group has developed a method to estimate the optimal energy from the quasielastic (QE) barrier distribution [5,6]. From the systematic studies of the relation between the QE barrier distribution and the fusion-evaporation cross section σ_{ER} for the hot-fusion reaction systems with an actinide target, the optimal reaction energy for maximizing σ_{ER} was found to be slightly larger than the average Coulomb barrier height B_0 obtained from the QE barrier distribution [6]. Furthermore, it was also pointed out that the side-collision energy B_{side}, which leads to a compact configuration of the colliding nuclei by touching along the short axis of the prolately-deformed target nucleus, deduced from the experimental B_0 value, is in good agreement with the optimal energy of the experimental σ_{ER} [6].

In our latest study [7], we measured the QE barrier distribution of ^{51}V+^{248}Cm, using a gas-filled recoil ion separator GARIS-III at a recently upgraded Superconducting RIKEN Heavy Ion LINAC (SRILAC) facility. The energy corresponding to the B_{side} was derived from the B_0 value determined from the present experiment, and the optimal reaction energy was estimated based almost purely on experimental evidence. Using the optimal energy obtained in this study, an experiment to synthesize element 119 is currently in progress at RIKEN.

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2022. Oct. 7. (Friday)

Laser Spectroscopy of the Heaviest Elements at SHIP at GSI

7 Oct
9:00am

Andrea Raggio[1], Sebastian Raeder[2], Andrew Mistry[3], Antoine de Roubin[4], Arno Claessens[4], Barbara Sulignano[5], Bradley Cheal[6], Brankica Andelic[7], Charlie Devlin[6], Christoph E. Düllmann[8], Danny Münzberg[9], Dieter Ackermann[10], Elisa Romero Romero[11], Elisabeth Rickert[11], Emmanuel Rey-Herme[5], EunKang Kim[12], Fedor Ivandikov[13], Francesca Giacoppo[14], Herve Savajols[10], Hessberger Fritz-Peter[14], Iain Moore[15], Jekabs Romans[4], Jeremy Lantis[16], Jessica Warbinek[17], Klaus Wendt[18], Magdalen Anna Kaja[19], Marine Vandebrouck[5], Matou Stemmler[16], Michael Block[11], Mustapha Laatiaoui[20], Nathalie Lecesne[21], Oliver Kaleja[22], Pierre CHAUVEAU[10], Piet Van Duppen[23], Premaditya Chhetri[24], Rafael Ferrer-Garcia[13], Sandro Kraemer[25], Simon Sels[4], Steven Nothhelfer[3], Thomas Walther[26], Tom Kieck[27], Vladimir Manea[28], Werner Lauth[29]

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Laser spectroscopy is a versatile tool to unveil fundamental atomic properties of an element and information on the atomic nucleus. Up to the chemical element fermium (Z=100), a limited number of long-lived isotopes can be produced in macroscopic amounts through irradiation of actinide samples in reactors where they undergo neutron capture and successive beta decay. Heavier elements and more exotic isotopes of the lighter elements are only accessible through fusion-evaporation reactions at minute quantities and at high energies, hampering their study by optical spectroscopy. However, the heaviest elements are of particular interest as their electron shell is strongly influenced by electron-electron correlations and relativistic effects changing the electron configuration and thus, the chemical behavior [1,2]. Furthermore, subtle changes in the atomic transition for different isotopes of the same element allow fundamental nuclear information to be inferred.

An exploration of the region of the heaviest elements with laser spectroscopy became possible with the RAdiation Detected Resonance Ionization Spectroscopy (RADRIS) technique. Here, recoils from fusion-evaporation reactions, which were transmitted by the velocity filter SHIP at GSI Darmstadt, are stopped in high-purity argon gas and collected onto a thin filament. After re-evaporation, the released neutral atoms are probed by two-step resonance laser ionization. The so created photo-ions were then guided to a detector where they were identified by their characteristic alpha decay. After the first identification and characterization of a strong atomic ground-state transition in ^{254}No [3] detailed studies on further nobelium isotopes were performed [4].

Here, we will present advancements and recent results of the RADRIS technique along with future prospects for laser spectroscopy of the heaviest elements. This includes the application on decay-daughter products of nobelium enabling the study of the fermium isotopes $^{248-250}$Fm, and with a dedicated detector setup also the long-lived isotope ^{254}Fm ($T_{1/2}$=3.24 h). The setup's performance was furthermore optimized with respect to the filament increasing the total efficiency for the search of atomic levels in heavier elements such as lawrencium (Z=103). A first experimental campaign for the search of an atomic level in ^{255}Lr was recently performed. Next steps include the extension of the RADRIS method to more exotic isotopes and the continuation of the level search in lawrencium (Z=103) as well as developments for higher spectral resolution spectroscopy. For the latter a dedicated setup was recently commissioned combining the efficient stopping and neutralization from the RADRIS technique with the high resolution of in-gas-jet spectroscopy [5,6]. Laser spectroscopy in the low-density and low-temperature regime of the jet enables higher resolution in the spectroscopy while the continuous operation and swift evacuation of the gas cell using electrical fields will allow us to address shorter-lived isotopes and isomers as, e.g., the lower lying 266 ms K-isomer in ^{254}No.

7 Oct
9:20am

Progress towards the EDM3 instrument at FRIB: A tool for studying radioactive molecules embedded inside cryogenic solids

Jochen Ballof[1], Nicholas Nusgart[2], Peyton Lalain[2], Mia Au[3], Reinhard Heinke[3], Simon Stegemann[3], Maximilian Schuett[3], Sebastian Rothe[3], Jaideep T. Singh[2]

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[3] *CERN*

The Facility for Rare Isotope Beams (FRIB) at Michigan State University has recently commenced operation and delivered first radioactive ion beams to its users [1, 2]. Besides its portfolio of fast, stopped, and re-accelerated beams, isotope-harvesting techniques are being developed to exploit isotopes that are otherwise lost to the beam dump [3]. The study of radioactive molecules receives increasing attention due to their enhanced sensitivity to fundamental symmetry violations and Beyond Standard Model physics [4].

In this contribution, we introduce the FRIB-EDM3-instrument which is currently under construction. The setup was designed to study polar radioactive molecules (like RaF) in transparent cryogenic solids by laser spectroscopy with the EDM3-method [5]. The efficient ionization of harvested radioisotopes from aqueous phase is pursued with a spray-ionization method [6]. Subsequently, the molecular ion beam is analyzed by mass-to-charge ratio by a quadrupole mass filter and neutralized in a charge-exchange cell before its implantation in a solid argon matrix. We will present the design of the instrument and report on the progress of its construction.

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Status of the JetRIS apparatus for laser spectroscopy of the heaviest elements

7 Oct 9:40am

Matou Stemmler[1], Julian Auler [2], Michael Block [3], Premaditya Chhetri [4], Arno Claessens [4], Christoph E. Düllmann [5], Rafael Ferrer [4], Francesca Giacoppo [6], Manuel J. Gutiérrez [7], Fedor Ivandikov [8], Magdalen Anna Kaja [9], Oliver Kaleja [10], Tom Kieck [11], EunKang Kim [12], Nina Kneip [13], Sandro Kraemer [14], Mustapha Laatiaoui [15], Jeremy Lantis [16], Nathalie Lecesne [17], Vladimir Manea [18], Danny Münzberg [19], Steven Nothhelfer [20], Sebastian Raeder [21], Jekabs Romans [4], Elisa Romero Romero [3], Herve Savajols [22], Simon Sels [23], Dominik Studer [9], Barbara Sulignano [24], Piet Van Duppen [25], Marine Vandebrouck [26], Thomas Walther [27], Jessica Warbinek [28], Felix Weber [9], Klaus Wendt [29], Alexandra Zadvornaya [30], Antoine de Roubin [23]

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Laser spectroscopy measurements can provide information about fundamental properties of both atomic and nuclear structure. These measurements are of particular importance for the heaviest actinides and superheavy elements, where data are sparse. Recent resonance-ionization-spectroscopy experiments at GSI, Darmstadt, Germany, have focused on in-gas-cell measurements using the RADRIS technique [1,2], successfully measuring a strong ground-state transition in $^{252-254}$No [3]. However, the limited spectral resolution of these measurements hampers the precision, and eventually renders determining the nuclear moments and spins impossible. Furthermore, the subsequent collection and measurement cycle limits accessible isotopes to those with lifetime of at least about 1 s. To overcome these limitations, a new JetRIS apparatus has been constructed to perform laser spectroscopy of atoms in a hypersonic jet [4]. In JetRIS, the highly energetic recoil ions are slowed down in argon gas and guided by electric fields to a heated filament for neutralization. They are then extracted by the gas into a hypersonic gas jet. This gas jet provides a low-density and low-temperature environment, which will improve the spectral resolution by about an order of magnitude to hundreds of MHz [5]. In addition, it allows the continuous operation for fast extraction, giving access to short-lived nuclei.

In the near future a narrow-bandwidth and high-repetition-rate titanium:sapphire laser system will be added to the existing state-of-the-art, narrow-bandwidth dye laser system. This combination will ensure complete versatility and highest performance [6]. The setup was recently commissioned at the GSI within the FAIR phase-0 program. The obtained performance of the apparatus and the accompanying laser system will be discussed along with the future perspectives in the talk.

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Development of the collinear laser spectroscopy system for the study of unstable nuclei at BRIF facility

7 Oct
10:00am

Xiaofei Yang[1], Shujing Wang [1], Shiwei Bai [1], Yongchao Liu [1], Peng Zhang [1], Yinshen Liu [1], Hanrui Hu [1], Hongwei Li [2], Bing Tang [3], Baoqun Cui [3], Chuangye He [3], Xie Ma [3], Qite Li [1], Jiahao Chen [1], Kai Ma [1], Lisheng Yang [1], Ziyao Hu [1], Weiliang Pu [1], Ying Chen [1], Yangfan Guo [1], Zeyu Du [1], Zhou Yan [1], Fulong Liu [3], Haoran Wang [3], Guoqing Yang [3], Yanlin Ye [1], Bing Guo [3]

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Collinear laser spectroscopy is a powerful tool for the study of the basic properties, such as the spins, magnetic moment, electric quadrupole moments and charge radii, and the related structure of exotic nuclei far from β-stability line [1]. In order to study these properties of unstable nuclei at Radioactive Ion-beam Facility in China, we have developed a collinear laser spectroscopy (CLS) system, which has been tested by using the stable Ca ion beams produced from a laser ablation ion source [1]. This CLS system has been recently installed at the Beijing Radioactive Ion-beam Facility (BRIF) [2]. The first successful on-line commissioning experiment of this system was performed by measuring the hyperfine structure of stable (39K) and unstable (38K) ion beams, in the continuous mode, produced at BRIF facility. This on-line experiment demonstrates the overall functioning of this CLS system, which opens new opportunities for laser spectroscopy measurement of unstable isotopes at BRIF and other radioactive ion beam facilities in China.

In this talk, the technique details of the CLS setup and the offline/online commissioning experiments, together with the on-going development of the collinear resonance ionization spectroscopy and RFQ cooler buncher, will be presented. The future scientific prospect of the CLS setup at BRIF will be discussed.

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7 Oct
10:50am

First experimental campaign at the new fragment separator ACCULINNA-2: superheavy 6,7H isotopes elucidated

E.Yu. Nikolskii [1], I.A. Muzalevskii[2], A.A. Bezbakh[2], V. Chudoba[2], S.A. Krupko[3], S.G. Belogurov[4], D. Biare[3], A.S. Fomichev[5], E.M. Gazeeva[3], A.V. Gorshkov[3], L.V. Grigorenko[6], G. Kaminski[7], M. Khirk[8], O. Kiselev[9], D.A. Kostyleva[10], M.Yu. Kozlov[11], B. Mauyey[12], I. Mukha[9], Yu.L. Parfenova[3], W. Piatek[7], A.M. Quynh[13], V.N. Schetinin[11], A. Serikov[3], P.G. Sharov[2], N.B. Shulgina[14], S.I. Sidorchuk[3], R.S. Slepnev[3], S.V. Stepantsov[3], A. Swiercz[15], P. Szymkiewicz[15], G.M. Ter-Akopian[5], R. Wolski[3], B. Zalewski[7], M.V. Zhukov[16]

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Recently the extremely neutron-rich systems 7H, 6H were studied in the direct 2H(8He, 3He)7H and 2H(8He, 4He)6H transfer reactions [1-3] with a 26 AMeV secondary 8He beam produced at the new ACCULINNA-2 fragment separator [4]. The missing mass spectra and center-of-mass angular distributions of 7H(6H), as well as the momentum distributions of the 3H fragment in the 7H(6H) frame, were reconstructed.

A solid experimental evidence is provided that the resonant states of 7H are located in its spectrum at 2.2(5) and 5.5(3) relative to the 3H+4n decay threshold.

Also, there are indications that the resonant states at 7.5(3) and 11.0(3) MeV are present in the measured 7H spectrum. Based on the energy and angular distributions obtained for the studied 2H(8He, 3He)7H reaction, the weakly populated 2.2(5)-MeV peak is ascribed to the 7H ground state (g.s.). It is highly plausible that the firmly ascertained 5.5(3)-MeV state is the 5/2+ member of the 7H excitation 5/2+ – 3/2+ doublet, built on the 2+ configuration of valence neutrons. The supposed 7.5-MeV state can be another member of this doublet.

The measured missing mass spectrum of 6H shows a broad bump at $\sim 4-8$ MeV above the 3H+3n decay threshold. This bump can be interpreted as a broad resonant state at 6.8(5) MeV. The obtained spectrum is practically free of the 6H events below 3.5 MeV (center-of-mass cross section is less than 5 μb/sr in the 5-16 deg. angular range). The steep rise of the 6H missing mass spectrum at ~ 3 MeV allows to derive the lower limit for the possible resonant-state energy in 6H to be 4.5(3) MeV. According to the paring energy estimates, such a 4.5(3) MeV resonance is a realistic candidate for the 6H g.s.. The obtained results confirm that the decay mechanism of the 7H g.s. is the "true" (or simultaneous) 4n emission. The resonance energy profiles and the momentum distributions of fragments of the sequential 6H$\rightarrow$ 5H(g.s.)+n $\rightarrow$ 3H+3n decay were analyzed by the theoretically-updated direct four-body-decay and sequential-emission mechanisms. The measured momentum distributions of the 3H fragments in the 6H rest frame indicate very strong "dineutron-type" correlations in the 5H ground state decay.

In addition, the proton and deuteron pickup reactions 2H(10Be,3He)9Li and 2H(10Be,4He)8Li were studied for the first time in the same setup with 44 AMeV 10Be radioactive beam. These measurements were motivated as test reactions to control the calibration and resolution over excitation energy for the studied 7H and 6H systems.

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7 Oct
11:10am

New fast-timing γ-ray detector system in Korea: KHALA

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The lifetimes of excited nuclear states play an important role in nuclear structure. These many-body quantum dynamic information are crucial particularly for understanding the nuclear shell structure. For instance, the excited states of nuclei near magic numbers provide evidence of the changes in shell structure from a single-particle nature to collective nature. Therefore, the measurement of the lifetimes of the excited state may give a perspective on overall features of nucleon interactions and subsequently the shell and shape structure of nuclei.
Recently, exotic rare-isotope beams far off the β-stability line were available, and the various state-of-the-art detectors and relevant electronics were developed. With such advances in technology, the fast-timing measurement has attracted much attention. The timing measurement requires more sophisticated and difficult technique compared to the energy measurement. A $LaBr_3$(Ce) inorganic scintillator is one of the optimal materials for this scientific purpose because of its great light yield and very short time response. For this reason, the construction of the $LaBr_3$(Ce) detector system became popular in the field and FATIMA [1] is one of the successful cases.

In Korea, a new fast-timing γ-ray detector system, Korea High-resolution Array of $LABr_3$(Ce) – KHALA, is being developed to measure such a short lifetime which is typically in a range of a few tens of picoseconds to a few nanoseconds. The KHALA is comprised of 36 $LaBr_3$(Ce) scintillator detectors with a 1.5-inch diameter and 1.5-inch height crystal size, particularly dedicated for the fast-timing response. In this talk, the development of the KHALA and its performances such as the energy resolution, timing response, and detection efficiency will be introduced in detail. Moreover, future experimental plans will be also discussed.

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Status report of in-flight recoil separators RITU and MARA

7 Oct
11:30am

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The gas-filled in-flight separator RITU at Jyväskylä, Finland, has been recently re-commissioned. A new focal plane instrumentation has been constructed and set-up at the RITU focal plane. It shares the same dimensions with the MARA focal plane which enables the use of same detectors and vacuum parts in both. Alongside the instrumentation the RITU recommissioning results and the brief operational principle will be presented.

The in-flight recoil mass spectrometer MARA has been used successfully over many years. The main objective has been the study of the neutron deficient nuclei close to the proton drip line and nuclei around the N=Z line. Several new isotopes and proton emitters have been identified in the decay studies at the focal plane and new nuclear structure information extracted via in-beam studies utilizing MARA and the Jurogam Ge-detector array. A new scintillator detector, Tuike, has been taken in use at the focal plane to improve the identification of weakly produced isospin-multiplet members under study by detecting high-energy betas. In addition to the brief overview of these type of MARA experiments, the description of charge plunger set up, able to probe lifetimes of highly converted transitions in heavy nuclei, will be given.

7 Oct
11:50am

KoBRA Wien Filter: Specifications and Project Status

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A Wien Filter is one of the key components in ion optics also known as a velocity separator. It consists of a dipole magnet generating a magnetic field, and an electrostatic dipole in the gap of the magnet generating an electric field perpendicular to both the magnetic field and the beam axis. The electric and magnetic fields are properly adjusted to obtain expected ion beams with a certain velocity.

Rare Isotope Accelerator complex for ON-line experiments, RAON, is a new RI beam facility in South Korea nearing completion including Korea Broad acceptance Recoil spectrometer and Apparatus, KoBRA, which will produce low-energy radioactive ion beams. KoBRA has been established and tested with radioactive fission source in 2021, and will be commissioned with an ion beam of ˜ 20 MeV/nucleon delivered from RAON. One of the main purpose of KoBRA is to separate and to identify low-energy rare isotopes using products from the nuclear reaction such as multi-nucleon transfer.

Recently, a new project at Center for Exotic Nuclear Studies (CENS) has been launched to introduce a Wien Filter in the KoBRA beamline, and this KoBRA Wien Filter (KWF) will play a significant role to enhance the isotope separation performance in beam production of KoBRA. Its specifications were determined based on the optimal ion optics of KoBRA to produce a low-energy beam, especially, the beams less than about 5 MeV/nucleon suitable for nuclear astrophysics experiments. The project is in the manufacturing phase and we expect that it will be installed within 2023.

In this talk, we will present the current status of KWF development and the details of its specifications as well as the ion optics of KoBRA with KWF. We will also discuss about future plans for the RI beam production and separation in KoBRA.

New applications of positron-emitting nuclei in medical imaging and treatment at GSI

Invited
7 Oct
2:00pm

Sivaji Purushothaman[1], Emma Haettner [1], Daria Kostyleva [2], Peter Dendooven [3], Christoph Scheidenberger [4], Hans Geissel [4], Bernhard Franczak [2], Daria Boscolo [2], Christian Graeff [2], Felix Horst [2], Christoph Schuy [2], Ulrich Weber [2], Timo Dickel [4], Vasyl Drozd [5], Christine Hornung [2], Erika Kazantseva [6], Natalia Kuzminchuk-Feuerstein [2], Ivan Mukha [2], Chiara Nociforo [2], Stephane Pietri [2], Claire-Anne Reidel [2], Heidi Roesch [7], Olga Sokol [2], Helmut Weick [2], Jianwei Zhao [8], Katia Parodi [9], Marco Durante [10], Super-FRS Experiment Collaboration , BARB Collaboration

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In comparison to protons, carbon ion radiotherapy (CIRT) offers a promising treatment alternative due to its prominent Bragg peak, reduced lateral scattering, and high linear energy transfer (LET). Due to these characteristics, a higher conformal dose deposition to the tumor volume is possible, while sparing as much healthy tissue as possible. In 1994, the National Institute of Radiologic Sciences (NIRS) in Japan began the first CIRT, at HIMAC in Chiba, followed by Gesellschaft für Schwerionenforschung (GSI), Darmstadt, Germany, in 1997, and thereafter by other facilities.

One of the major challenges of CIRT is the lack of accuracy in the image guidance systems. This is due to the inherent uncertainties in the conversion from X-ray computer tomography (CT) data to particle stopping powers, ranges, positioning of the patient, and anatomical changes. Uncertainty in the location of dose deposition requires larger safety margins for the tumor in the treatment planning, which results in irradiation of a larger volume of normal tissue. An established technique for the range verification in CIRT is positron-emission tomography (PET) imaging of the positron emitters produced by the fragmentation of the target and projectile. GSI was the first CIRT facility to establish the "online" PET as an online range verification tool in a clinical setting. However, the use of PET for range verification in heavy ion therapy with stable beams has the drawbacks: the mismatch of the activity peak to the Bragg peak of the treatment beam, and the low photon statistics compared to that of a positron emitter. A promising way forward is to use short-lived positron emitters as therapy beams. The technique was pioneered by Lawrence Berkeley National Laboratory and at the early stage of ion-beam therapy investigations at GSI, the scope of the in-beam PET imaging using radioactive ion-beam was investigated. Further developments at HIMAC, Japan, are focused on the positron-emitting isotopes of carbon and oxygen for therapy. To date, the technique has been limited to use as a low-dose probe beam for pre-treatment range verification due to the orders of magnitude lower yield of secondary radioactive ions as compared to the primary beam intensity.

With the recent intensity upgrade of accelerators, the fragment separator FRS at GSI is now capable of delivering secondary beams of short-lived positron emitters with therapy-relevant intensities. Taking advantage of this upgrade, a European initiative on biomedical applications of radioactive beams (BARB) was launched at GSI in 2021, which aims at pre-clinical validation of in-vivo beam visualization and ion-beam therapy with positron-emitting isotopes of carbon and oxygen. As a first step towards this goal, PET imaging studies of high-intensity beams of positron-emitting isotopes of oxygen and carbon at therapy-relevant energies were performed at the symmetric branch of FRS. The secondary beams, with a purity of ¿98% and intensities of up to 108 ions/sec, were implanted into tissue-equivalent plastic, PMMA, to produce high-quality images with a dual-plane PET scanner. The main aim of this experiment was to explore the possibility of real-time range verification using positron-emitting therapy beams and conventional PET. The results on the impact of ion-optical modes of FRS (e.g., mono-energetic, achromatic) and the beam intensity on PET image quality were investigated.

The goals within the coming years are the full characterization of the dose profiles of high-intensity radioactive ion beams in preparation for pre-clinical studies, the development of a dedicated BARB detector that combines PET and prompt gammas to achieve submillimeter resolution, and the first small animal irradiation with positron-emitting beams. Another major development within the project was the setting up of the beam transport from FRS and the medical cave (cave-M) of GSI where the abovementioned experiments are conducted. The first successful delivery of the fragment beams from FRS to biomedical experiments at cave-M opened up a new application for radioactive ion beams at GSI. An overview of the field and the results from the first year of the BARB project will be presented.

This work is supported by European Research Council (ERC) Advanced Grant 883425 BARB.

Characterization and optimization of ISOLDE beams of Dy/Tb isotopes for medical applications

7 Oct
2:30am

Ulli Köster, Dinko Atanasov[1], Katerina Chrysalidis[2], Thomas Day Goodacre[3], Karl Johnston[4], Vladimir Manea[5], Bruce Marsh[4], Maxime Mougeot[6], Sebastian Rothe[7], Christoph Seiffert[4], Frank Wienholtz[8], Deyan Todorov Yordanov[9], the ISOLDE-RILIS team

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[9] *CERN, IJClab*

Terbium is unique for medical applications since different Tb isotopes emit α, β^-, β^+ or γ-radiation or conversion and Auger electrons respectively. In particular, the quadruplet of Tb isotopes ^{149}Tb, ^{152}Tb, ^{155}Tb and ^{161}Tb can cover together all diagnostic and therapeutic modalities in nuclear medicine [1]. Their identical chemical and biochemical properties assures fully exchangeable *in vivo* behavior.

While the neutron-rich ^{161}Tb is reactor-produced, the neutron-deficient Tb isotopes are accelerator-produced, mainly by (p,x n) reactions on enriched Gd targets or by spallation of Ta targets combined with on-line or off-line isotope separation at CERN-ISOLDE or CERN-MEDICIS respectively [1-5].

Due to the relatively low volatility of trivalent lanthanides, the Ta target and the ionizer line have to be kept at high temperature. Dysprosium is more easily released than terbium, therefore at ISOLDE the collections of Tb isotopes are performed *indirectly*, by resonantly laser ionizing the Dy precursor isotopes. However, there is considerable background of surface ionized isobars and "pseudo-isobars" of oxide sidebands. The latter can actually dominate the overall activity and dose rate of collected samples and should be minimized to limit the personal dose during handling, transport and chemical separation of the collected Tb samples.

On-line measurements with the ISOLTRAP multi-reflection time-of-flight mass spectrometer (MR-ToF MS) [6,7] and off-line γ-ray spectrometry of collected test samples were used to characterize the beam composition at masses 149, 152 and 155 as function of target temperature, ionizer temperature and laser settings respectively.

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Production of innovative radioisotopes for medical applications at the CERN-MEDICIS facility

7 Oct
2:50am

Alexandre Dorsival[1], Ana-Paula Bernardes[1], Cyril Bernerd[2], Bernard Crepieux[1], Bruce Marsh[1], Charlotte Duchemin[2], Edgars Mamis[3], Elodie Aubert[1], Eric Chevallay[1], Fabio Pozzi[1], Francesco Riccardi[1], Jean-Yves Rinchet[1], Joachim Vollaire[1], João Pedro Ramos[4], Julien Thiboud[1], Katerina Chrysalidis[1], Laura Lambert[1], M Deschamps[5], Moazam Khan[6], Nabil Menaa[1], Pascal Fernier[1], Philippe Bertreix[1], Qaiser khan[7], Reinhard Heinke[1], Richard Catherall[1], Slavka Prvakova[1], Stefano Marzari[1], Thierry Stora[1], Thomas Elias Cocolios[8], Umar Khalid[6], Valentine Fedosseev[1]

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Since its commissioning in December 2017, the CERN-MEDICIS facility has been providing non-conventional radioisotopes for research in nuclear medicine. Benefiting from decades of experience in the production of radioactive ion beams and in the mass separation process from the ISOLDE facility at CERN, CERN-MEDICIS quickly became a worldwide key player on the supply of of novel medical isotopes dedicated to research in the fields of cancer imaging, diagnostics, and radiation therapy.

The isotope production is performed using a target either placed in the radiation field generated from the 1.4 GeV proton beam delivered by the CERN Proton Synchrotron Booster scattered from the ISOLDE target, or using radioactive sources provided by one of the MEDICIS collaborating facilities. This later mode of operation allows CERN-MEDICIS to be among the only facilities running during CERN's long shutdowns. Following laser and/or surface ionization, acceleration/extraction and mass separation, the isotope of interest is implanted on metallic foils. The resulting high molar (specific) activity product undergoes a radiochemistry purification process and is finally shipped to one of the medical laboratories from the MEDICIS collaboration (medicis.cern).

After a few years of operation, collections have been performed on a large panel of radionuclides such as ^{128}Ba ^{149},^{152},^{155}Tb, ^{153}Sm, ^{167}Tm, ^{169}Er, ^{175}Yb, ^{191}Pt, and ^{255}Ac. A couple of milestones have been achieved on the output of the facility, such as the collection of 500MBq of ^{175}Yb, and a total separation efficiency of 50% reached in 2020 for ^{167}Tm. These collections led to notable recent successes such as in-vivo and first proof-of-concept preclinical results in targeted radionuclide therapy obtained for high molar activity ^{175}Yb and ^{153}Sm products.

Constant developments are ongoing, such as innovative targets designs, in-target molecular formation to improve the release of specific isotopes, laser development in the dedicated MELISSA laboratory, study of new implantation materials, and post-collection radiochemistry. Finally, CERN-MEDICIS is at the heart of the *European* *medical isotope programme* PRISMAP, which consists in a 23 institutes consortium, aiming at accelerating the research in nuclear medicine by providing a single hub for the medical community supplied with innovative radionuclides with high purity grade (prismap.eu, H2020 grand #101008571).

Poster Session

Test Results and Current Status of the RISP 28GHz ECR ion source

PS-1-1

Yonghwan Kim[1]

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The RISP 28GHz ECR ion source was transferred from the temporary test site to the RISP main site in 4Q 2019. Installation and precision alignment were completed in 1Q 2020. Cryostat cool-down started in October 2021 due to site mechanical equipment condition. In the operation of the superconducting electromagnet, after several training procedures, Ba.max=3.0T was reached in June 2021. The beam extraction test was conducted under such magnetic field conditions. For the relative verification of the ion source performance, Ar13+ beam was selected as the target beam, and a test was conducted to maximize the beam current. As a result, a beam current of 100euA, which was less than the 1st stage target of Ar13+ 250euA, was drawn. For further improvement of the ion source, points to be improved are summarized in this paper.

PS-1-2

TULIP project: first on-line result and close future

Vincent BOSQUET[1], Pascal JARDIN[1], Pierre CHAUVEAU [1], Samuel DAMOY [1], Pierre DELAHAYE [1], Mickaël DUBOIS [1], Fadil MANSSOUR [1], Mathieu LALANDE [1], Clément MICHEL [1], Jean-Charles THOMAS [1], Marion MACCORMICK [2]

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The TULIP project* aims to produce radioactive ion beams of short-lived neutron-deficient isotopes by using fusion-evaporation reactions in an optimized Target Ion Source System (TISS). The first step consists of the design of a TISS to produce rubidium isotopes. It was tested with a primary beam of 22Ne@4.5 MeV/A irradiating a natNi target at the SPIRAL1/GANIL facility in March 2022. Rates of 76,78Rb were measured as well as an exceptionally short atom-to-ion transformation time for an ISOL system, of the order of 200 µs.

The second step of the project aims at producing neutron deficient short-lived metallic isotopes in the region of 100Sn. A “cold” prototype has been realized to study the electron impact ionization in the TISS cavity and a “hot” version is under construction to prepare an on-line experiment expected in 2023. Obtained results and the project status will be presented.

* : https://anr.fr/Projet-ANR-18-CE31-0023

Understanding radioactive ion beam production at TRIUMF-ISAC through yield measurements and simulations

PS-1-3

Corina Andreoiu[1], Peter Kunz[2], Fatima H. Garcia[1], Hua Yang[2], Jens Lassen[2], Valery Radchenko[2]

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The high-intensity proton beam of the TRIUMF H^- 500 MeV cyclotron offers unique opportunities to produce rare isotopes by irradiating a variety of targets. In particular, the ISAC (Isotope Separation and ACceleration) facility [1] provides the infrastructure to deliver customized rare ion beams to experiments in the fields of nuclear structure, astrophysics, medicine, and material science. ISAC target stations can host a wide range for targets, from graphite to uranium carbide. Each target material generates a unique set of isotopes through nuclear reactions induced by the proton beam.

A continuous effort is underway to develop new radioactive ion beams (RIB) and improve their intensity or purity, properties that depend strongly on the type of target, operating conditions, the ion source, and beam transport efficiency. However, isotopically pure RIBs are not always achievable due to limitations on the selectivity of the ion source and the resolution of mass separation. Instead, RIBs can consist of a variety of atomic and molecular isobars with beam intensities sometimes spanning over more than 10 orders of magnitude.

An important tool to characterize RIB compositions, using α, β and γ spectroscopy, is the ISAC Yield Station [2]. Most of the close to 1000 radioactive isotopes and isomers so far documented in the TRIUMF Isotope Database [3] have been identified and quantified by it. Other diagnostic tools include Faraday cups, channeltron detectors and, more recently, the TITAN MR-TOF mass spectrometer, which can identify extremely weak RIB [4].

The yield data on various target-ion-source combinations, operational settings and mass-over-charge ratios in the database is complemented by theoretical production rate simulations based on FLUKA and GEANT4 models, two of the most common tool kits for calculating the interactions of high-energy particles with matter. Both experimental and theoretical data sets provide valuable input for RIB development and experiment planning.

In this contribution we will discuss examples where the combination of yield data with GEANT4 simulations is used to determine the release time of an element from a target, to plan an experiment and understand the correlation between alternative production pathways for certain isotopes and the measured yield:

• The average release time of francium from a uranium carbide target was determined by minimizing the ratios of measured yield over calculated production rate for the relatively long-lived isotopes $^{211-213}$Fr and the short-lived ^{214}Fr to a time-dependent release model [5].

• The collection of up to 370 MBq of ^{155}Tb for nuclear medicine research showcases how simulation data helps to determine the choice of ion source to maximize the yield of precursors of ^{155}Tb and how yield results are used to determine the length of RIB collection and cool-down periods [6].

• Recent upgrades of the GEANT4 model for ISAC targets provided quantitative information on direct and indirect production channels for ^{239}Pu from ^{238}U. Comparison with the measured ^{239}Pu yield helps to gain a better understanding of the release properties of neptunium and plutonium [7].

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Radioactive ion source experimental study for ISOL@MYRRHA

PS-1-4

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MYRRHA [1,2] (Multi-purpose hYbrid Research Reactor for High-tech Applications) will be the world's first large-scale Accelerator Driven System project at power levels scalable to industrial systems. In parallel to the reactor, ISOL@MYRRHA [3] will produce Radioactive Ion Beams (RIBs) using the Isotope Separation On-Line (ISOL) technique. The isotope production will be increased by using a high intensity primary beam over a long period while maintaining high-quality RIBs. Higher atom flux produced prevalently affects the ISOL system, one part in particular is the ion source. An ion source adapted to these new conditions has to be developed before the start of the new accelerator for ISOL@MYRRHA at SCK CEN.

A surface ion source is chosen as a first source to test because of its reliability and simple design. This source was already studied theoretically and experimentally by Kirchner [4] and has shown that one of this source key element is the temperature, which is why those sources are also called hot cavity. To understand the hot cavity's behaviour, finite element thermal-electric simulations were performed with ANSYS [5,6]. To start, a heating system study with experimental results from the SPES project [7] was reproduced. Then, this concept was modified by: electrically insulating the source from its support, adding a feedthrough and transforming a passive thermal screen into an active part. With this heating system upgrade, the ion source temperature profile can be improved, especially at its exit where high temperature is expected to play a crucial role in ion production and extraction. This heating system upgrade was assessed through thermal-electric simulation [6] and now needs to be validated experimentally. A prototype of this novel hot cavity configuration will be tested at a heating test stand at SCK CEN: first through thermal-electric test to assess the hot cavity's temperature behaviour, but also test the prototype reliability, then the ion source properties will be tested with offline ion extraction tests.

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What's NEXT? A setup for the production and separation of neutron-rich nuclei

PS-1-5

Julia Even[1], Xiangcheng Chen [1], Arif Soylu [2], Paul Fischer [3], Karpov Alexander [4], Vyacheslav Saiko [5], Jan Saren [6], Moritz Schlaich [7], Thomas Schlathölter [1], Lutz Schweikhard [8], Juha Uusitalo [6], Frank Wienholtz [7]

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Neutron-rich **EX**otic nuclei around the neutron shell closure at $N=126$ and in the transfermium region are accessible via multinucleon **T**ransfer reactions which features relative high cross-sections. However, the wide angular distributions of the multinucleon transfer products lead to experimental challenges in their separation and identification.

In order to overcome these obstacles, we are building the NEXT experiment at the AGOR facility in Groningen. The AGOR cyclotron is capable to deliver high intense heavy ion beams at energies suited for transfer reactions. The production target for the transfer reactions is places inside a 3-T solenoid magnet. The bore of the solenoid is 160-cm long and 90-cm wide. Within this volume the transfer products are separated according to their magnetic rigidities. The isotopes of interest are focused to a gas catcher where they are slowed down. From the gas catcher the ions are transferred and bunched by a novel stacked-ring ion guide [1] into a Multi-Reflection Time-of-Flight Mass Spectrometer (MR-ToF MS) [2]. The MR-ToF MS provides isobaric separation and allows for precision mass measurements. We will present an overview of the NEXT setup and the planned experimental program.

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PS-1-6

Optimized production and extraction of medical grade Ac-225

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^{225}Ac radiopharmaceuticals are being developed for the treatment of certain distributed cancers using targeted alpha therapy. However, supply shortages of ^{225}Ac itself strongly constrain the progress of such research [1]. As a consequence, a number of accelerator-based production routes are being pursued at different facilities worldwide. Alongside the ^{226}Ra(p,2n)^{225}Ac and ^{226}Ra(γ, nβ) ^{225}Ac reactions, the high-energy (>70 MeV) proton spallation of natural Thorium or Uranium targets can produce high in-target yields of ^{225}Ac [2,3]. Once ^{225}Ac has been produced in an irradiated target, it must then be extracted, limiting how much can be recovered. Presently this is performed by radio-chemical separation of the target or by mass separation of a radioactive ion beam.

According to the target material and the primary beam energy, different quantities of ^{225}Ac, its β-decay parent ^{225}Ra ($t_{1/2}$ = 14.9d), and the long-lived contaminant ^{227}Ac ($t_{1/2}$ = 21.8y) are produced. As a consequence, the subsequent separation technique must be adapted to the irradiation conditions to maximize extraction efficiency, in addition to satisfying facility constraints, isotopic purity requirements for drug manufacture and hospital waste handling [4].

In this work the simulated in-target yields of ^{225}Ac, ^{225}Ra and ^{227}Ac for irradiations at different proton-spallation-capable facilities are presented. The optimum techniques for subsequent ^{225}Ac separation, with consideration to efficiency and isotopic selectivity, are then discussed. Emphasis is put on the method of resonant laser ionization and mass separation, for which an upper efficiency bound and isotopic selectivity have recently been experimentally determined for separations performed at the CERN MEDICIS facility [5]. The results are interpreted in the context of the global effort to scale up ^{225}Ac production to meet the increasing demand for this isotope.

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PS-1-7

Reconditioning of the Leuven Isotope Separator as a test bench for radioactive ion beam development

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Radionuclides have already revolutionised the field of nuclear medicine and the diagnosis and treatment of cancer patients. Some of the novel medical radionuclides can only be made using the Isotope Separation Online technique (ISOL). The radioactive species collected for medical applications need to be pure, which requires mass separation [1]. Terbium has been identified as a particularly promising radionuclide – there is a quadruplet of isotopes that can be used for both diagnostics and therapy [2]. However, there is a bottleneck when it comes to terbium production – it is hard to extract from the target and ionize. This is the most significant in the timeline needed to extract the alpha-emitter, Tb-149, which would fill the current gap in the targeted alpha therapy, but has a half-life of only 4.1h.

Consequently, it is key to understand the ion source and ensure that it works not only with high efficiency but that it can also handle the high throughput needed for medical samples. At KU Leuven, we are working on refurbishing the Leuven Isotope Separator, a mass separator previously used for implantations of radioisotopes in solid-state samples for characterization of their properties and Mössbauer spectroscopy [3]. We aim to use it to systematically study the CERN FEBIAD ion source VADIS to help overcome the terbium production bottleneck [4]. In the past couple of years, the machine has undergone some significant updates and has been adapted to integrate the target ion source units used at ISOLDE, CERN. In the future, it is also intended to be used as a test bench for the sources developed for ISOL@MYRRHA and to investigate radioactive sample separation, such as K-40 for muonic X-ray spectroscopy.

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Molecular ion beams at CERN-ISOLDE – development and facilities

PS-1-8

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The CERN-ISOLDE facility at CERN uses the Isotope Separation On-Line (ISOL) method to provide experiments with radioactive ion beams (RIBs). Isotopes are produced in thick targets and must undergo diffusion and effusion before reaching the ion source, where they are then ionized. Forming volatile molecules with the radioactive species of interest is a technique occasionally used to efficiently extract beams of refractory elements [1-4] and to eliminate isobaric contamination by mass-separation on a molecular sideband. Certain radioactive molecules are candidates for studies of fundamental symmetry violations and new physics beyond the standard model [5,6]. Recently, radium fluoride was studied using laser spectroscopy at ISOLDE [7], demonstrating experimental capabilities to study radioactive molecules at RIB facilities.

Developments from the ISOLDE targets and ion sources are essential to characterize ionization and breakup channels of these molecular species of interest, facilitating delivery as molecular ion beams. For fragile molecules with low dissociation temperatures, alternative methods of production are needed [8]. For all molecular species, separation and identification are required for systematic studies. The ISOLDE off-line facilities are upgraded in terms of production, manipulation, and detection of molecules, thus enabling systematic studies on the formation, ionization and dissociation of molecular beams. We will present the infrastructure and developments for molecular beam studies as well as first results of ongoing offline developments for molecular beams.

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PS-1-9

A laser ablation carbon cluster ion source for high accuracy mass measurements with an MR-TOF-MS

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At the FRS Ion Catcher (FRS-IC) at GSI Darmstadt, Germany, short-lived nuclei produced with the fragment separator FRS are thermalized in a cryogenic stopping cell (CSC) and measured with a high-resolution multiple-reflection time-of-flight mass spectrometer (MR-TOF-MS).

The MR-TOF-MS at the FRS-IC has been used for mass-measurement with resolving powers of up to 1,000,000 (FWHM) and accuracies down to 210^8. To further improve the mass measurement accuracy, calibrants over a broad mass range are needed for systematic error studies on the 10^9 level with the MR-TOF-MS. Furthermore, calibrants with a mass close to the mass of the ion of interest are advantageous. For these purposes, a laser ablation carbon cluster ion source (LACCI) has been built and commissioned, capable of providing calibrant ions in the mass range of 36 u to 240 u. LACCI uses a laser with a repetition rate of up to 100 Hz (532 nm diode pumped solid state laser) in order to match the needs of the MR-TOF-MS. This repetition rate is two orders of magnitude larger than the one of existing systems and requires special designs to ensure stable long-term (week) operation.

A study of the repetition rates, laser optics (laser spot size, laser energy), target movement and ion optics (ion transfer efficiency) has been carried out. The development of LACCI and the commissioning results of LACCI coupled with a quadrupole mass filter and the MR-TOF-MS for long-term operation will be reported in this contribution.

The new Batch Mode Ion Source (BMIS) for stand-alone operation of the ReA reaccelerator at the Facility for Rare Isotope Beams (FRIB)

PS-1-10

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The reaccelerator ReA at FRIB has been used for a successful science program with rare isotopes produced by projectile fragmentation. In the transition of the FRIB laboratory from providing rare isotopes from the National Superconducting Cyclotron Laboratory's Coupled Cyclotron Facility to full FRIB operation with its high-power superconducting linear accelerator and new rare isotope production facilities, a stand-alone capability for long-lived and stable isotopes has been added to ReA operation. A Batch Mode Ion Source (BMIS) has been built largely following the designs and concepts developed and employed at ISOLDE/CERN. BMIS consists of an oven, where rare isotopes with relatively long lifetimes are placed, coupled to an oven ion-source (OIS) system mounted to a front-end with optics elements for beam transport. ISOLDE target modules with a VADIS ion source are being used for the OIS. With the OIS biased at the maximum of 60 kV, ion beams are extracted and delivered to the stopped-beam area and the Electron Ion Beam Trap (EBIT) of the ReA facility. At present BMIS has been used to successfully produce and deliver stable and rare isotopic beams of 10Be, 7Be, 32Si, 26Al, 58Fe, 86Kr, 120Sn, and 50Cr for experiments. This contribution describes BMIS, how the desired rare isotopes were produced, and how the delivered beam was purified and identified with techniques involving the ReA linac.

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PS-1-11

The new CERN-ISOLDE fast tape station

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For the operation of a radioactive ion beam (RIB) facility the employment of a suitable decay spectroscopy setup is essential. CERN-ISOLDE uses for more than 40 years a tape station as primary asset for the determination of RIB production yields and as diagnostic tool for beam commissioning before each physics experiment as well as radioactive beam development. To improve timing and noise characteristics, a new fast tape station (FTS) was built and initially commissioned in 2018 [1], and recently relocated to its final position within the CERN-ISOLDE central beam line. The FTS consists of a vacuum chamber with four detector positions, accommodating an in-beam β-detector, a 4π β-detector [2], a high purity germanium detector for the measurements of γ-rays and a silicon detector for α-particles. We report here on the technical details in terms of hardware and software, the first operational years of the FTS and future upgrades and extension of the yield measurement capabilities and capacities at ISOLDE.

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Radioactive ion beams of Sb isotopes

PS-1-12

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Because of the magic number Z = 50, there is great scientific interest in isotopes of tin and the neighboring indium and antimony nuclei. At CERN-ISOLDE, radioactive ion beams (RIBs) of In, Sn and Sb are typically produced from uranium carbide (neutron-rich) and lanthanum carbide (neutron-deficient) targets. While for the former two elements yield data is available, to date, no data has been reported for Sb isotopes using 1.4-GeV protons [1]. During the 2018 and 2021 experimental campaigns at CERN-ISOLDE, Sb RIBs were produced with 1.4-GeV protons from the Proton Synchrotron Booster using UC_X and LaC_X targets and resonant laser ionization. As a result, both proton- and neutron-rich RIB production yields could be determined via β-, γ-decay and ion beam current measurements. In addition, isomeric ratios of Sb, as well as Sn during earlier experimental campaigns, were determined by means of collinear laser spectroscopy. The respective results will be presented in this contribution.

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PS-1-13

Expanding RIB Capabilities at the Cyclotron Institute: 3He-LIG Production with an Isobar Separator

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The primary goal of a new facility, TAMUTRAP, at the Cyclotron Institute, Texas A&M University, is to look for physics beyond the standard model by searching for a possible scalar currents contributing to the weak interaction. In particular, we will measure the β-ν correlation parameter, $a_{\beta\nu}$, in several $T = 2$ superallowed β-delayed proton emitters initially confined in a novel and unique cylindrical Penning trap.

This trap has been designed to be very large (180-mm inner diameter) so that β-delayed protons of up to 4.25 MeV energy are fully contained radially by the 7-T field of the magnet. As the proton-rich radioactive-ion beams (RIBs) needed for the TAMUTRAP program are developed at the Cyclotron Institute, we have commissioned the facility by demonstrating the ability to perform precise mass measurements using offline ion sources. Once RIB is successfully produced and transported to TAMUTRAP, we will be uniquely suited to observe the β-delayed proton decays of ^{20,21}Mg, ^{24,25}Si, ^{28,29}S, ^{32,33}Ar and ^{36,37}Ca with 4π collection of the βs and delayed protons.

In order to produce the proton-rich RIBs for TAMUTRAP, a new production target and beamline is being constructed at the Cyclotron Institute. The high-intensity primary beam of ^{3}He from the K150 cyclotron will impinge on a heavy target with the reaction products collected and extracted using the light-ion guide (LIG) technique. Following this we have designed LSTAR, a compact, high-resolution isobar separator to purify the RIBs in order to prevent overloading TAMUTRAP's RFQ cooler and buncher with contaminants.

An overview of the He-LIG and LSTAR systems and their expected performance will be presented, largely within the context of the TAMUTRAP science program.

Latest improvements of the SPIRAL1 facility at GANIL

PS-1-14

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Since 2001, the SPIRAL1 facility has been providing post-accelerated radioactive beam by the ISOL method. Over the last decade, SPIRAL1 has been improved to provide beams of condensable elements, by using a combination of a FEBIAD-type ion source (to produce 1+ ions) and a PHOENIX ECR charge breeder (to transform 1+ ions into N+ ions for post-acceleration).

The FEBIAD ion source has undergone several minor design changes over the years in order to increase its efficiency and reliability over week-long experimental campaigns. The latest design of our Target Ion Source System (TISS) has achieved argon ionization efficiencies up to 25% and has been able to sustain 15% efficiency for 8 continuous days with excellent stability. Progress has also been made on the SPIRAL1 charge breeder (SP1CB), which has been fitted with a second HF amplifier. This new TWT amplifier can be used alone (variable single frequency heating) or in combination with a Klystron amplifier (double frequency heating) to help us control the charge-state distribution at the exit of the SP1CB and therefore the range of energy and intensity available after post-acceleration with the CIME cyclotron.

Recent results regarding these improvements will be presented.

PS-1-15

Development of direct on-line temperature measurements of ISAC targets at TRIUMF

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Target temperature plays a crucial role in the performance of an ISOL target. At TRIUMF an optical technique has been developed and implemented on-line for direct temperature measurements simultaneous with beam heating. In this setup the light emitted by a hot target through the ionizer opening is collected via a set of optics and coupled into a spectrometer [1]. The method uses a spectrometer equipped with a near infrared (NIR) diffraction grating and a Hamamatsu InGaAs detector that allows continuous visualization of near-blackbody emission spectra representative of the target temperature. The spectrometer and its custom collection optics are calibrated using a Thorlabs Stabilized Tungsten-Halogen calibration source and the sample temperature is determined from fitting the recorded thermal spectrum using Planck's law and an emissivity model. The paper will report the method, the hardware and the test results correlating the measured target temperature with thermal simulation results and isotope release ratios measured at the yield station[2].

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Beam measurements in high-current ECR ion source

PS-1-16

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Korea University(KU) has installed 14 GHz Electron Cyclotron Resonance Ion Source (ECRIS) for researches on material science and bio science. The high voltage platform of KU-ECRIS had been upgraded form 10kV to 30kV. During the upgrade, the geometry of the plasma electrode is changed due to arc discharge occurred in cone-shaped plasma electrode. According to positions of plasma electrode, effects of the total current and currents of multi charged ions were investigated. The informations about position of plasma electrode and beam size were obtained using SIMION simulations. The comparison of experimental results between total current and current of multi charged ions with two faraday cups will reported in this paper. We will introduce currents status of beam measurements for the KU-ECRIS.

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PS-1-17

Status of the target development for the ISOL system

Jaewon Jeong, Sangho Na

Uranium carbide (UCx) and silicon carbide (SiC) have been developed for the target materials of the RAON ISOL system. Based on the CERN technology, the fabrication process of the UCx target has been developed with the goal of the low density (¡ 3 g/cm3) and the large diameter (50 mm). It is planned to be used for the proton beams up to 10 kW and the prototype of the UCx target was fabricated, currently. The SiC target has been fabricated with different densities and grain sizes to compare the isotope release property and the thermal stability. it would be used for the commissioning experiment to produce the rare isotope beam (RIB) using 70 MeV of Cyclotron at the end of 2022.

On the feasibility of online terbium extraction at ISOL@MYRRHA.

PS-1-18

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Terbium is an element that has four isotopes with interesting properties for medical applications, ^{149,152,155,161}Tb[1]. These radioisotopes are however far from being sufficiently accessible, thereby hindering the pursuit of research on radiolabelling as well as clinical or preclinical investigations. Their lack of market availability is explained by difficulties in producing these radioisotopes with high purity and specific activity. While ^{161}Tb can be produced using neutron capture in nuclear reactors the other isotopes require other production pathways which are not yet fully developed for large scale production[2]. For ^{149,152,155}Tb, a production route involving the ISOL technique is under study within the Tb-IRMA-V project, from a consortium between SCK CEN, KU Leuven and CERN with the aim towards producing terbium based radiopharmaceuticals. The ongoing R&D towards the production and extraction of these isotopes from an ISOL target at the ISOL@MYRRHA facility will be covered in this contribution.

As a first step in developing the ISOL technique for the production of Tb radioisotopes, different possible target material candidates have been investigated and the most suitable target materials have been identified by comparing cross sections of these target materials as well as their vapour pressures as compared to the isotopes of interest. In a second step, the release of Tb radioisotopes or their precursors from the identified target materials have been studied. The purpose of this was to release as much of the isotope of interest as possible, while maintaining a high degree of selectivity to keep other releases to a minimum. The following techniques and their merits were considered: 1- isotope release with molecular sidebands 2- separation inside a temperature-controlled transfer-line, using differences in adsorption enthalpy. Combined, these studies allow to estimate the production capacity of the neutron-deficient Tb radioisotopes at the ISOL@MYRRHA facility.

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PS-1-19

Numerical ionization model for the TRIUMF FEBIAD and the experimental comparison of ion beam properties

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TRIUMF currently uses a FEBIAD ion source to generate 1+ radioactive ion beams of noble gases, halogens, or molecules. Typically, the offline ionization efficiency obtained for a TRIUMF FEBIAD source tends to be ¡ 1 % for 40Ar+, however, other ISOL facilities report values ranging from 10-25%. To understand the limitation and optimize performance for both ISAC and the upcoming ARIEL facility, a numerical and experimental campaign has been performed. The numerical model predicts a spatial distribution of ions, and their simulated extraction can explain observables such as emittance and energy spread. Using numerically optimized operation parameters yields immediately in 10-fold improvements of the experimental 40Ar+ ionization efficiency. However, when operating the source at more extreme parameters, the measured ionization efficiency even ranges from 15% to 30% before the source fails. To mitigate these particular failures modes, the numerical model has further been used to perform optimization for reliability and better efficiencies. With the proposed geometrical optimization, it is expected to provide a reliable operation and therefore maintain high experimental efficiencies.

The ISAC Target and Ion Sources Outlook: Facility Reliability Improvements

PS-1-20

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The ISAC facility has been producing radioactive ion beams for more than 20 years, however the infrastructure is beginning to age and revitalizing highly activated equipment poses challenges. Here we report on a plan to refurbish the ISAC infrastructure for increased reliability and with upgrades to improve science output. The main focus of this plan is the refurbishment of the ISAC target modules, which are crucial to the production of radioactive ion beams, but which suffer from high radioactive exposure and frequent mechanical interventions. Common failure modes and deficiencies, learned through years of experience at ISAC, will be identified and addressed in order to help ISAC continue to meet its goal of >93% availability of targets and ion sources. In addition to the module upgrades, supporting infrastructure, equipment and processes must also be improved, as part of a facility-wide approach to addressing ISAC's future.

PS-1-21

A new laser ionisation scheme resulting in a 10-fold yield increase of Pb isotopes at ISOLDE

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The development of new, more efficient laser ionisation schemes at the ISOLDE Resonance Ionisation Laser Ion Source (RILIS) directly impacts the yields of radioactive beams at ISOLDE [1]. Additionally, laser ionisation schemes which only use solid-state Titanium:Sapphire (Ti:Sa) lasers, are easier to maintain over long run durations [2]. An added bonus is reduced set up time, if the scheme ties in well with the laser availabilities. This contribution will present the development of a new laser ionisation scheme for lead (Pb), which has improved efficiency over the previously used scheme, facililitated the laser setup and reduced maintenance requirements.

The previously used Pb ionisation scheme at RILIS was developed using a dye laser system pumped with copper vapour lasers. It includes two resonant excitation steps and a non-resonant transition to the ionisation continuum with a 532nm Nd:YVO laser. The ionisation efficiency of stable Pb isotopes measured with this scheme was about 3%. This work will present a new three-step scheme which has been developed using only Ti:Sa lasers - one frequency quadrupled and two within the fundamental Ti:Sa wavelength range. The UV-step utilised in this scheme has a lower wavelength (217nm) than was previously feasible to generate at RILIS due to challenges with continued stable UV-generation. This UV-instability has been investigated and solved. A comparison between the old and the new scheme for lead revealed a factor 10 improvement of the laser ionisation efficiency. A 10-fold increase of isotopic yield over the ISOLDE database values was determined by applying the new scheme for delivery of $^{187-208}$Pb radioactive ion beams to the COLLAPS experiment.

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Development of targets with tailor-made microstructure at CERN-ISOlDE

PS-1-22

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At CERN-ISOLDE, among the main technical challenges for the production of radioactive ion beams (RIBs) is the design of target materials for in-target isotope production via nuclear reactions to allow for fast diffusion and effusion of the produced species for delivery to ISOLDE users. This requires a compromise between density and pore structure, while maintaining the required levels of thermal stability to limit sintering and maintain these properties in online separator conditions. Thus, a dedicated program has been recently launched at CERN-ISOLDE to develop target materials with tailor-made microstructure and to study their characteristics with respect to improved isotope release, RIB yield and microstructural stability. Since carbide and oxide targets constitute more than 70% of the operated targets [1], main focus lies on the development of nanosized UCx and LaCx target materials, with increased surface areas, fine pore structure and greater thermal resistance. In addition, this program explores the development of nanosized and highly porous ceramic materials such as ZrO2. Currently, fiber-based structures are occasionally used at CERN-ISOLDE, which are however prone to sintering effects. By exploiting electrospinning[2] and freezecasting techniques[3], nanofiber-based materials with minimized contact points that otherwise foster sintering, and highly porous materials with oriented pore structure for fast effusion paths are developed for optimized target performance. In this contribution, we will give an overview over these development efforts and present first results.

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PS-2-1

High beam-power RI production project at SCRIT electron scattering facility

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Electron-beam-driven RI separator for SCRIT (ERIS) [1] was constructed as an online isotope separator (ISOL) system that is dedicated to produce a radioactive isotope (RI) beam for the SCRIT (Self-Confinement RI Target) electron scattering facility [2] at RIKEN RI Beam Factory. Electron scattering is one of the best ways to accurately understand the internal structure of atomic nuclei. The aim of this facility is realization of electron scattering experiment with unstable nuclei, for which the target nuclei of 108 ions/s are required.

In ERIS, the photofission of uranium driven by the electron beam is used for the RI production. 43 self-made uranium-carbide disks are stacked to be the target. The disk is approximately 0.8 mm thick and 18 mm in diameter. The amount of uranium is approximately 0.65 g/disk. The uranium-carbide disks are irradiated by 150 MeV electron beam accelerated by a microtron. Recently, the yields of ^{132}Sn and ^{137}Cs beams extracted from ERIS were achieved to 2.6×10^5 ions/s and 8.0×10^6 ions/s with 15-g and 28-g uranium targets and a 10-W electron beam, respectively [3].

SCRIT experiment requires to increase the yield of RI beam by a factor 100. We plan to upgrade the power of electron beam to 2 kW. At the same time, we need to develop a high-power resistant system for ERIS such as a remote handling system for ERIS, treatment of targets after irradiation, radiation shields, and so on. In this contribution, we will report of present status of ERIS and an upgrade plan in the SCRIT facility.

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Characterization of release properties from ISOL target

PS-2-2

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Several offline tests have been performed to investigate release properties of ISOL target materials and their geometric configurations, with the objective of understanding and improving the radioisotope release performance of online ISOL targets.

This contribution gives an overview of the general procedure which has been implemented at TRIUMF, consisting of activating ISOL target material samples with high-energy protons, heating up the material in a resistive oven and measuring the activity of selected isotopes before and after the heating stage to estimate their release fraction at the set temperature. Several tests were performed on metal, graphite and carbide samples produced with different synthesis procedures, highlighting the effects of their microstructure on the release fraction. The results of these experiments will be presented, which proved to be a reliable source of information that feeds into the choice of target materials to be used or studied further in limited online beam time devoted to target and ion source development.

A second set of experiments was performed to investigate the macroscopic effusion of isotopes through the macroscopic voids inside an ISAC target container, to better characterize and understand the driving forces of the effusion processes. Literature resources about effusion in ISOL targets usually refer to mathematical models or extrapolation of results from single pellet experiments, while this work focuses on measuring directly the rate of the effusion process in a macroscopic and representative configuration i.e. the ISOL target itself. An overview of the procedure will be given, and the initial results comparing spatial distribution of isotopes in a metal foil ISOL target will be presented and compared to each other.

PS-2-3

Parasitic material irradiation damage studies at ISAC/TRIUMF

Alexander Gottberg[1], Ferran Boix Pamies[1]

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The high-power driver beams of future accelerator facilities pose thermomechanical challenges for the design of beam intercepting components that need to dissipate increased power densities and sustain higher radiation damage levels. Additionally, target components and adjacent materials will also suffer from high fluxes of ionizing radiation, often degrading critical mechanical properties. In RIB facilities, new target stations will need to use novel designs and materials in order to enhance yields and exploit the increased isotope production rates from high-power driver beams. Usually, no experimental data is available for the evolution of material properties in these conditions. In this context, the use of parasitic irradiations in already existing RIB facilities, as well as future high-power facilities offer a relevant and efficient test methodology.

TRIUMF's main cyclotron delivers 480 MeV, 100 A proton beams (6.25 x 1014 protons/second) to the Isotope Separator and Accelerator facility (ISAC) for the production and delivery of RIBs by the ISOL method. The RIB targets have a total stopping power of only 50-80 MeV resulting in a residual high-power proton beam downstream of the target. A material sample irradiation setup has been developed and commissioned to parasitically irradiate material candidates for proton beam windows, as well as de-novo design material candidates for enhanced resilience to radiation damage, while another setup off beam is used to irradiate vacuum seals and polymeric materials for future ARIEL targets and other high-power accelerator applications.

The commissioning methodology and the experience gained with the irradiation and manipulation of parasitic attachments at ISAC will be presented together with collected results this far.

The present status of ISOL module and Remote handling system for Isotope Separation On-line facility in RISP.

PS-2-4

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The Rare Isotope Science Project (RISP) plans to produce rare isotope using Isotope Separation On-line (ISOL) facility. The rare isotopes are produced in Target Ion Source (TIS) system by a 70 MeV proton beam incident on target via the proton-induced fission. RISP adopt module system controlled by remote handling system to handle and maintain the TIS system. The module system consists of proton, TIS and RI module, and was designed to be applied high voltage and current, water cooling system, beam optics and diagnostic. The key components of remote handling system are a precision crane, hot-cell, manipulator and etc. In this presentation, the current status of ISOL module system are introduced, along with remote handling system.

PS-2-5

Design and Fabrication of Beam Dump System for the RAON SR Facility in Korea

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The beam dump system was designed and fabricated to absorb residual protons of the SR facility at the Rare Isotope Science Project in Korea. In the SR facility, protons with 600 MeV energy are incident on the graphite target to generate muons, and only about 10% of the power is absorbed in the graphite target and the remaining power is either absorbed in the beam dump or used to break binding energy. This study introduces a design method a beam dump that safely absorbs residual protons when the current of the facility is 165 A (100 kW). The material of the beam dump was determined to be oxygen-free copper(OFC) in consideration of thermal conductivity and corrosion resistance. The target performance of the beam dump system was set such that the temperature, stress and effective dose did not exceed 200 °C (softening temperature of OFC), 69 MPa (yield stress of OFC) and 5 Sv/hr, respectively. In order to achieve this performance, absorbed energy at beam dump and effective dose were simulated using MCNP6 code. Temperature and stress were simulated using ANSYS code. As a result, the beam dump consisted of six copper plates, and the maximum temperature and stress were evaluated at 154°C and 61 MPa, respectively. After that, a structure for the designed beam dump and movement alignment was manufactured and fabricated in the facility.

First in-gas laser spectroscopy with S3-LEB

PS-5-1

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The S^3-LEB (Super Separator Spectrometer-Low Energy Branch) is a low energy radioactive ion beam installation dedicated to the study of exotic nuclei, which is currently under commissioning as a part of the GANIL-SPIRAL2 facility [1]. High intensity primary beams delivered by the superconducting LINAC of SPIRAL 2 will allow increased production rates of nuclei by fusion evaporation reactions and thus will facilitate the exploration of the neutron-deficient and heavy-mass extremes of the nuclear chart. The reaction products will be separated by the recoil separator S^3 and will be delivered to the LEB installation coupled to the S^3 focal plane [2].

S^3-LEB is a gas cell setup where the radioactive ions of interest are thermalized, neutralized and then selectively laser ionized either inside the gas cell or in a hypersonic gas jet environment created after the gas cell using a De-Laval nozzle. It is then followed by radiofrequency quadrupole ion guides, which allow efficient transmission of the ions to a Multi-Reflection Time of Flight Mass Spectrometer (MR-TOF MS) for further beam purification and detection. A decay spectroscopy station, Spectroscopy Electron Alpha in Silicon Box Counter (SEASON), will also be coupled to the LEB installation expanding its capabilities. First offline results from S^3-LEB were published recently presenting the commissioning of laser systems and conditions for optimum operation of the ion guides obtained using an alkali ion source [3].

Here we present the progress in the offline commissioning of the S^3-LEB setup highlighting the results obtained after coupling the gas cell to the ion guides and the first laser spectroscopy in the gas cell/jet, as well as the transport of laser ions, bunching and trapping in the MR-TOF MS. For the offline tests and in preparation of one of the day-1 experimental campaigns, a filament was heated in the gas cell for the production of stable isotopes of Erbium. A first view of the performance of the installation in preparation for S^3 experiments will be given.

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Construction of the Superallowed Transition Beta-Neutrino Decay Ion Coincidence Trap

PS-5-2

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Nuclear beta decays provide a unique avenue for testing the electroweak part of the Standard Model through precision measurements. Physics beyond the Standard Model would manifest itself in these transitions through a variety of possible effects including a non-unitarity of the Cabibbo-Kobayashi-Maskawa quark mixing matrix, scalar or tensor currents, and interactions involving right-handed neutrinos. Probing these various effects in superallowed mixed beta decay transitions can be done through precision measurement of the beta-neutrino angular correlation parameter. As such, we are currently constructing at the Nuclear Science Laboratory of the University of Notre Dame the Superallowed Transition Beta-Neutrino Decay Ion Coincidence Trap (St. Benedict). St. Benedict will take a radioactive ion beam produced by TwinSol, thermalize it in a large volume gas cell, then transport it through two separate, differentially-pumped, volumes using a radio-frequency carpet and a radio-frequency quadrupole (RFQ) ion guide before injecting it into an RFQ trap to create cool ion bunches for injection into the measurement Paul trap. The status of the St. Benedict development will be presented. This work is supported by the US National Science Foundation under grant PHY-1725711.

PS-5-3

Charge Breeding Experiment of Stable Ion Beams in EBIS Charge Breeder for RAON Facility

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The Electron Beam Ion Source (EBIS) charge breeder is utilized to produce highly charged ions in Isotope Separation On-Line (ISOL) system of Rare isotope Accelerator complex for On-line experiments (RAON).

Offline and online tests of EBIS are performed by using stable ion beams, which are Cs, Sn, and Na. $^{133}Cs^{1+}$ ions from a test ion source were injected into the EBIS to measure the breeding effect with the electron beam whose current can be used up to 2 A in various breeding times. The resultant relative abundance of $^{133}Cs^{27+}$ was 23.9 % and the extraction energy per charge was 49.3 keV/q. A charge breeding test of 120Sn ions was also carried out. The Sn ions were extracted from a laser ion source of the ISOL system. The charge fraction of $^{120}Sn^{24+}$ was 23.7% and the energy per charge with 50 keV/q, and the ions were transported to the end of ISOL beam line which is the start position of reacceleration. These results fulfilled the input beam condition of the RFQ accelerator (A/q ¡ 6 and 10 keV/u). To find the operating condition for light ions, we are performing the optimization with Na ions. Additionally, the highly charged ion beam with various pulse lengths is required for some experiments, so the length of the beam from the EBIS should be possible to be determined. In the experiment, $^{133}Cs^{27+}$ ions charge-bred by the EBIS are extracted with a pulse length up to 10 ms (FWHM) by applying the time-varying voltage on drift tubes in the breeding section when they eject.

The main experimental results will be described in this presentation.

Development of a Reference Trap to Diagnose RFQ-CB of the heavy ion accelerator RAON

PS-5-4

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The Radio Frequency Quadrupole Cooler Buncher (RFQ-CB) of the heavy ion accelerator RAON is a device that cools the incoming ion beam and sends it out in the form of a bunch. In order to analyze the trapped ions and improve the performance of the RFQ-CB, we built a reference trap which is the miniaturized version of RFQ-CB. The reference trap consists of RF and DC electrodes in an octagon chamber, a helium supply system, viewports, and a Ba+ ion source to make a condition similar to RFQ-CB. Because Ba+ ion has strong electric dipole transition at visible wavelength (455 nm), an extended cavity diode laser (ECDL) will be used to make fluorescence from the trapped ion bunch and eventually measure the temperature of the cooled ions. Imaging of the ion bunch with precise timing will be developed to analyze the performance of the RFQ-CB at various helium buffer gas pressure and RF/DC voltage. The development details of our reference trap will be presented at the conference.

PS-5-5

Preparation of the Iron Spectroscopy at PAL-XFEL with the UNIST-EBIT

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UNIST (Ulsan National Institute of Science and Technology) built a device called an Electron Beam Ion Trap (EBIT) to generate and study highly charged ions (HCI). In January 2022, preliminary experiments were carried out on highly charged argon ions. EBIT was delivered to Pohang City, where the PAL-XFEL is located, and successfully connected to the hard X-ray beam-line. Over the two R&D beam times, we study the highly charged argon with a monochromatic photon beam from the PAL-XFEL (Pohang Accelerator Laboratory X-ray Free Electron Laser). In this work, we present past argon spectroscopic measurements as well as preparation progress for our next iron experiment.

Beam diagnostics for RISP ISOL beamline system

PS-5-6

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RISP's ISOL beamline system is for separation of specific ion beam generated by the target ion system (TIS) and transfers it to the downstream experimental device and linear accelerator. The commissioning using the stable isotope ion beam has been started in 2021, and a commissioning using the radioisotope ion beam is planned at the end of 2022. The beam diagnostic device is a key device that checks the performance of the beamline during ISOL beamline commissioning. In this presentation, the development status of the beam diagnostic device will be shown.

PS-5-7

Simulation, design and construction of cryogenic gas catcher for the MRTOF-MS at SHANS

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Heavy and super-heavy nuclei have been studied at the Institute of Modern Physics, Chinese Academy Sciences. In recent years, new neutron-deficient isotopes ^{205}Ac, $^{214-216}$ U and $^{220,222-224}$ Np were synthesized at the Spectrometer for Heavy Atom and Nuclear Structure (SHANS). In order to extend the studies, the multi-reflection time-of-flight mass spectrometer (MRTOF-MS) is under construction at the downstream of the SHANS for mass measurement and isobaric separation.

A cryogenic gas catcher is one of the key part of MRTOF-MS and being construction for collecting the fusion-evaporation products from SHANS. By using Monte-Carlo method, the geometry of the gas catcher, the thickness of aluminium degrader and the optimal gas pressure filled in the gas catcher have been calculated and estimated. The ion transport processes along the surface of RF carpet have been simulated and compared by using ion surfing transport method with different RF amplitude and frequency, wave amplitude and velocity, and push field strength. The mechanical design and assembly of the gas catcher have been completed and the testing progress is in progress.

In this conference, we will present the simulation results and design. The status of cryogenic gas catcher for MRTOF-MS will be also reported.

The Cyclotron Gas Stopper at FRIB getting ready for operations

PS-5-8

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Gas stopping of energetic projectile fragments has been an important pathway to science with unique stopped and reaccelerated beams at the National Superconducting Cyclotron Laboratory (NSCL) for more than a decade. The NSCL has transitioned into the recently opened Facility for Rare Isotope Beams (FRIB) in order to provide significantly more exotic and more intense exotic beams, prompting novel upgrades to the gas-stopping facility.

FRIB will continue to operate two linear gas-stopping cells to provide projectile fragments at low energy. In order to extract the lightest ions rapidly, which are difficult to stop efficiently in linear gas cells that are < 1m long, a gas-filled reverse cyclotron has been constructed. The device uses a ˜2.6T field superconducting cyclotron-type magnet [1] and helium gas to confine and bring the injected beam to a halt. The beam is transported to the center of the magnet by a traveling-wave RF-carpet system, extracted through the central bore with an ion conveyor and will be accelerated to <60 keV energy for delivery to the users.

Following construction and successful low-energy ion transport tests with an internal ion source [2], the cyclotron gas stopper was moved to an experimental vault and connected to the A1900 fragment separator at the NSCL (and now to the ARIS separator) with a dedicated momentum compression beamline. After a series of runs with primary beams to commission the new high-energy beam line and test the injection into the cyclotron stopper, a beam of ^{46}K fragments was stopped and extracted. The magnetic rigidity of the beam was reduced to match the acceptance of the Cyclotron stopper at ˜1.1 Tesla-meter inside the beam chamber, where ions came to rest in helium gas at up to 40 Torr pressure. Beta activity with a half-life of ^{46}K, detected at the end of the ion conveyor, proved successful extraction of this beam from the cyclotron stopper. A summary of the commissioning tests with high-energy beam and plans for integrating the device into FRIB's low-energy beam distribution network will be presented.

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PS-5-9

High-resolution mass measurements for the verification of particle identification at in-flight separators

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Nowadays, many experiments in the field of nuclear structure, fundamental interactions and nuclear astrophysics require the use of exotic nuclei. These rare isotopes can be produced with modern powerful accelerator facilities at several laboratories worldwide. These laboratories solve the problem of the inherent small production cross sections via high primary beam intensities and high energies. However, the successful production of exotic nuclei is only the first necessary step, the separation from the primary beam and from the abundant contaminants and the particle identification, by measurements of their properties are of equal importance.

At the FRS facility at GSI, exotic ions are produced, separated and identified in-flight. The Particle IDentification (PID) by proton number (Z) and mass number (A) can be performed with the FRS and its particle detectors applying the Bρ-ΔE-TOF method. At relativistic velocities, the verification of the selected bare ions can be easily performed with particle detectors via velocity (TOF), energy-deposition (ΔE) and magnetic rigidity (Bρ) measurements in coincidence. Still the separation and identification requires an elaborated absolute calibration. At lower velocities (300˜MeV/u), the heaviest fragments emerge from the target in different ionic charge states which makes an unambiguous PID very difficult.

Therefore, the fragment identification in-flight by the Bρ-ΔE-TOF method at these velocities can be verified by accurate high-resolution mass measurements. Note that each isotope has a unique signature in terms of the measured binding energy (mass excess). At the final focal plane of the FRS, the FRS Ion Catcher (FRS-IC) setup is installed where the ions-of-interest are stopped in a gas cell to perform accurate mass measurements. The mass measurements of the ions are performed with a multi-reflection time-of-flight mass spectrometer (MR-TOF-MS). In this way, the FRS-IC can provide an unambiguous isotope identification via high-resolution mass measurement. This method has been successfully applied with the combination of the FRS-IC and the in-flight separator FRS. The method is fast, sensitive and universal. A verification of the FRS PID by the MR-TOF-MS at the FRS-IC was proven in several experiment with ^{107}Ag, ^{124}Xe, ^{208}Pb and ^{238}U primary beams.

PS-6-1

Ion optical simulation for the NEXT solenoid separator at AGOR

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The NEXT project aims to study Neutron-rich, EXotic, heavy nuclei produced in multi-nucleon Transfer reactions[1]. Part of the NEXT setup is a 3T superconducting solenoid magnet with a 90-cm wide and 1.6-m long bore. The magnet will be used to focus the transfer products of interest and to separate those from unwanted by-products as well as from the unreacted primary beam.

We developed a Python code to simulate the paths of ions through the magnetic field of the solenoid. The goal of the simulation is to determine the optimal layout of the separator to achieve the highest transmission efficiencies and strongest background suppression. The simulation requires a realistic description of the magnetic field in- and outside the solenoid. For this purpose, we implemented an interpolated approach. The trajectories of the ions through the magnetic field are determined through their emitting angles and magnetic rigidities. Therefore, we implemented the calculation of the charge state distribution in the code. As input data, our code requires the differential cross-section, the kinetic energies, and the emitting angles of the transfer products. So far, we have studied two reactions[2,3] in order to optimize the configuration of the NEXT
separator:

- 136Xe+198Pt at 6 MeV/u to produce nuclei around the N=126 shell closure
- 48Ca+251Cf at 6.1 MeV/u to produce nuclei in the transfermium region

In this poster, we present an overview of our simulations and we highlight the most important results that determine the layout of the separator.

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Current status of a fast neutron TOF facility at RAON PS-6-2

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A fast neutron facility, called NDPS (Nuclear Data Production System), is being constructed for nuclear science and applications at RAON (Rare Isotope Accelerator complex for ON-line experiments) in Korea. The NDPS has been designed to provide both white and mono-energetic neutrons, using 98 MeV deuteron and 20 – 83 MeV proton beams with a thick graphite and thin lithium targets, respectively. The energy of neutron is determined by employing the time-of-flight (TOF) technique, along with a pulsed deuteron (or proton) beam with a repetition rate of less than 200 kHz. Fast neutrons are produced in the target room and are guided to the TOF room through a 4 m long neutron collimator consisting of iron and 5 % borated polyethylene. The neutron beam is monitored using a parallel plate avalanche counter and a micro-meh gaseous detector installed in the TOF room, so as to measure the energy and the position of neutrons. The present status of NDPS will be reported, together with the future plan.

PS-6-3

Simulation Studies for Beam Commissioning at FRIB Advanced Rare Isotope Separator

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The Facility for Rare Isotope Beams (FRIB) includes a powerful superconducting driver accelerator and an Advanced Rare Isotope Separator (ARIS). The ARIS collects and purifies the rare isotope fragments of interest for experiments in nuclear physics, nuclear astrophysics, fundamental symmetries, etc. ARIS consists of a vertical pre-separator and downstream horizontal separator section (C-Bend). Each section can provide a high-resolution separation alternatively. The resolution reduction due to the emittance induced by momentum compression can be avoided by isotope separation in different dispersive planes. Beam commissioning of ARIS for the first experiments was completed and demonstrated particle identification of fragments. The beam tuning in ARIS largely relies on numerical simulations since the limited space for diagnostics. We report the result of the beam trajectory correction, transverse matching, and beam-based misalignment studies at ARIS.

Generation of contaminant-like beams for magnetic spectrometer characterization

PS-6-4

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Characterizing a (high resolution) magnetic mass separator can be often tricky as it is difficult to find a stable ion source providing species with close enough masses to separate.

As these instruments perform a momentum separation (B rho = p/q), their mass and energy resolution are strictly the same at first order. One can use this property to characterize the mass resolution of a spectrometer through its energy resolution. Hence, multiple identical beams with close energies can be used to test a magnetic spectrometer in almost real conditions. The method we will present allows to populate an ion beam with multiple close and well-defined energies. It consists in using an arbitrary pulse generator to temporally change the acceleration potential of the ion source, and create a custom energy distribution, where the length of the pulse is the production ratio of the contaminant and the amplitude its relative energy (mass).

We will present the entire setup as well as results of mass-like separation on the DESIR High Resolution Separator.

PS-6-5

The DESIR facility at GANIL/SPIRAL2

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DESIR, the low-energy facility of GANIL/SPIRAL2 is presently in its final design phase. It will provide users with high-quality exotic beams at energies up of 60 keV. The call for tenders for the construction of the facility has been launched and construction should start in 2023.

The paper will present the physics case of the DESIR facility, its general layout and the instrumentation under construction or commissioning. The physics case is centred around three pillars: laser spectroscopy with the LUMIERE facility, ion trapping within DETRAP and the beta-decay experiments grouped in the BESTIOL collaboration. The experiments will address topics in nuclear structure physics, fundamental interactions, nuclear astrophysics and applications of nuclear techniques. One of the main assets of DESIR will be the availability of two complementary production sites for radioactive species (neutron-deficient and heavy nuclei with S3, light fragments with SPIRAL1) and a series of purification devices to provide isotopically pure beams to the users.

An innovative Superconducting Recoil Separator for HIE-ISOLDE

PS-6-6

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The development of radioactive beam facilities has unprecedently expanded our capacity to investigate the structure of the atomic nucleus and the nuclear interaction. The ISOLDE Scientific Infrastructure at CERN offers the widest range of low-energy radioactive beams [1]. The scientific program can be remarkably improved with the installation of an innovative spectrometer, the "Isolde Superconducting Recoil Separator" (ISRS), that will give very high mass resolutions and access to regions of the nuclear chart presently unknown [2]. The ISRS spectrometer is based on an innovative concept for particle storage, the Fixed Field Alternating Gradient Superconducting Mini-Ring (FFAG-SCMR), an array of iron-free superconducting multifunction Canted Cosine Theta magnets [3] cooled by cryocoolers, integrated into a compact storage mini-ring using Fixed Field Alternating Gradient focussing [4]. The present goal of the ISRS collaboration is to perform the necessary research to demonstrate the feasibility of building FFAG-SCMRs and their application to particle spectroscopy. A prototype of a multifunction iron-free SC magnet will be built (MAGDEM) and probed with heavy-ion beams to prove the working concept. In this contribution, an overview of the physics goals and ongoing technical developments will be presented and discussed.

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COLLINEAR LASER SPECTROSCOPY ON THE PALLADIUM ISOTOPIC CHAIN

PS-7-1

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The use of high resolution optical measurements of the atomic structure is at the forefront of modern subatomic physics. Laser spectroscopy provides model-independent nuclear data of nuclear spins, moments and charge radii across long chains of isotopes [1]. This allows the study of the evolution of nuclear observables versus particle number to probe shape deformation, configuration mixing and structural evolution effects.

The collinear laser spectroscopy setup [2] at the IGISOL facility [3] in the Accelerator Laboratory of the University of Jyv¨askyl¨a, has been used to perform measurements on palladium isotopes (Z=46) in the mass range A=98-118. Thanks to the chemically insensitive IGISOL ion-guide production method [4], it has been possible to reduce the existing gap in optical spectroscopy data below Z=50, created by the refractory character of these elements.

This contribution will present the latest results on laser spectroscopy measurements on the Pd isotopic chain. Special attention will be paid to the magnetic dipole and electric quadrupole moments. The main results of trends in the mean-square charge radii have recently been accepted for publication [5], nevertheless, new complementary results regarding the odd isotopes will be presented. These observables will be compared to state of the art theoretical calculations. Three different models for the interpretation of our data will be confronted, Large Scale Shell Model (LSSM), Fayans Energy Density Functionals (EDF) and Beyond-mean field calculations.

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PS-7-2

Studying negative ions at the CRIS experiment

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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 challenging [3]. With the collinear resonance ionization spectroscopy (CRIS) experiment at ISOLDE, negative ions can be produced via the double charge exchange process. 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 two-step excitation scheme of laser photodetachment followed by resonance ionization can be used.

Negative ion yield tests at CRIS will be carried out for polonium (Po) followed by francium (Fr) and uranium (U). After commissioning the spectrometer, EAs can be measured. Fr, the heaviest alkali metal, will require a two-step excitation scheme as mentioned above. This method has been successful for stable cesium (Cs) [4] and is currently being tested on stable rubidium (Rb).

In this contribution, results from the Po- 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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PS-7-3

Developments towards high-resolution laser spectroscopy of 235mU

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Among the numerous isomers hidden within the landscape of the nuclear chart, ^{235m}U is the second lowest in energy, with the lowest being the well-known ∼8-eV ^{229m}Th isomeric state. The study of these isomers via high-resolution laser spectroscopy provides a valuable insight into their nuclear properties, such as nuclear mean-squared charge radii and nuclear electromagnetic moments. This information presents a challenge to state-of-the-art nuclear and atomic theory and is therefore needed to improve the predictive capabilities and to benchmark present models. In this respect, the actinide region is of particular interest but it poses special production challenges.

Within this context, a measurement campaign has been started at the IGISOL facility [1], University of Jyväskylä, Finland, aimed at measuring properties of the ^{235m}U 76-eV isomeric state via high-resolution laser spectroscopy. This will be achieved with the IGISOL collinear spectroscopy beamline [2], in which a 30-kV accelerated ion beam is overlapped with a counterpropagating continuous wave laser beam, Doppler shifted to the resonance wavelength. The spectroscopic resolution achieved is sufficient to resolve hyperfine structures and isotope shifts, being close to the natural linewidth of the studied transitions. The production of a ^{235m}U beam will be achieved using a ^{239}Pu alpha-recoil source, developed at the Johannes Gutenberg University, Mainz. The isomer is populated via alpha decay from ^{239}Pu with a summed branching ratio close to 100\%. The source will be mounted in the IGISOL actinide gas cell [3,4] and ^{235m}U recoils will be stopped, thermalized and extracted in a helium gas flow. After acceleration and mass separation, bunched beams of ions will be formed in the radiofrequency quadrupole cooler (RFQ) and transported to the collinear laser spectroscopy beamline.

Before the isomer measurement, a full characterization of the suitable optical transitions is needed. A set of 12 ionic transitions in the wavelength range from 288 to 314 nm has been studied, using the three natural isotopes of uranium: ^{234}U, ^{235}U and ^{238}U. In parallel, the recoil sources have been characterized using a variety of material based analysis techniques, nuclear decay spectroscopy and ion counting methods to quantify the recoil ion yield. In this contribution, we will summarize these two aspects of the project and provide an outlook to the forthcoming isomeric measurement.

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PS-7-4

High-resolution laser ionization spectroscopy of actinides in a Supersonic Gas Jet

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Resonant laser ionization and spectroscopy are widely used techniques at radioactive ion beam facilities to produce pure beams of exotic nuclei and measure the mean-square charge radii, spins and electromagnetic moments of these nuclei. In such measurements on the heaviest elements it is, however, difficult to combine a high efficiency with a high spectral resolution. A significant improvement in the spectral resolution by more than one order of magnitude was demonstrated without loss in efficiency [1] by performing laser ionization spectroscopy of actinium isotopes in a supersonic gas jet. This novel spectroscopic method [2] is thus suited for spectroscopic studies of the ground- and isomeric-state properties of the hardly accessible actinide elements with an unprecedented spectral resolution and a high efficiency at radioactive beam facilities such as SHIP (GSI) and S3-LEB (GANIL).

Offline characterization studies at KU Leuven, dealing with the flow dynamics and the formation of supersonic jets produced by different gas-cell exit nozzles [3], and the characterization of a high-power, high-repetition rate laser system comprising multi- and single-mode lasers [4], have been carried out to optimize the performance of the technique. Furthermore, we plan on producing pure ion beams of the low-energy nuclear isomer in ^{229}Th to determine its lifetime and excitation energy in a series of experiments that will complement current and future measurements performed at ISOLDE (CERN).

In my talk, I will summarize the main results of off-line studies carried out at KU Leuven and will report on the implementation and prospects of the in-gas-jet resonance ionization method applied to very-heavy elements.

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Offline development for collinear laser spectroscopy at the SLOWRI facility

PS-7-5

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Collinear laser spectroscopy is a powerful tool to study nuclear properties such as electromagnetic moments, spin, changes in charge radius, and shape in ground or isomeric states along isotopic chains. At the radioactive isotope (RI) beam factory of RIKEN, the in-flight fragmentation separator called Big-RIPS has supplied intense RI beams. A helium gas-catcher called SLOWRI has been developed at the downstream side to stop and cool the high-energy fragment beams. The SLOWRI facility supplies slow and low-emittance ion beams of most elements. It is an attractive platform where nuclei that are not accessible from ISOL based RI facilities can be studied. Particularly short-lived isotopes from refractory elements are accessible. Consequently, collinear laser spectroscopy on isotopic chains of refractory elements is under preparation at the SLOWRI facility.

Towards online measurement on RI beams, we have prepared an offline setup and performed test measurements using singly charged barium isotopes. In this proof of principle Ba ions were produced continuously by surface ionization, extracted at 10 keV, mass-separated, and collinear laser spectroscopy was performed. A homemade external cavity diode laser (ECLD) was used to excite a strong optical transition in the ion at 455 nm and spectra of stable isotopes (A=132-138) were observed. Then we measured spectra of singly charged zirconium ions as a proof of principle for refractory elements. Ions were produced by pulsed laser ablation. A commercial Ti:Sa laser with second harmonic generation using a LBO crystal was used to excite a strong transition in the Zr ion at 357 nm. We observed spectra of all stable isotopes (A = 90-92, 94, 96) by photon counting in coincidence with the pulsed ion beam for 50 us to reduce background counts. An additional development is to use ion bunches from a multi-reflection time-of-flight mass spectrometer (MR-TOF), where bunch lengths of 40 ns are achievable for further improvements of the signal to noise ratio in collinear laser spectroscopy – which is critical to extend collinear laser spectroscopy to isotopes produced at low intensity.

PS-7-6

Present Status of Laser Ion Source Development at the RAON ISOL facility

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The Resonance Ionization Laser Ion Source (RILIS) system based on Ti:Sapphire lasers pumped by a Nd:YAG laser has been developed for the on-line laser ion source for a new heavy ion accelerator, RAON, in Korea. As a milestone of extraction of rare isotopes produced through uranium fission, double magic nucleus of ^{132}Sn is our first target. Thus, by employing a three-step resonance excitation scheme, the ionized stable isotopes of Sn have been successfully extracted and separated via a mass-separator magnetic system to test the performance of the RILIS setup at the off-line test facility [1] and the RAON ISOL facility. In the commissioning phase, the hot-cavity laser ion source in the ISOL facility will be tested and used to produce RI beams, e.g. Al isotopes using a SiC target with a 70 MeV proton beam.

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Development of the Collinear Laser Spectroscopy system in RAON

PS-7-7

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Rare Isotope Science Project (RISP) at Institute for Basic Science (IBS) has been carried out to construct a Rare isotope Accelerator complex for ON-line experiments (RAON). Collinear Laser Spectroscopy (CLS) system will be installed in RAON's ISOL beamline and is being developed for the study of basic nuclear properties such as nuclear spin, electromagnetic moment, and mean square charge radius using laser spectroscopy technology for stable and unstable ion beams. The RAON CLS system is a device that performs spectroscopic experiments through relative frequency modulation due to the Doppler effect by fixing the incident laser frequency and controlling the speed of the ion beam. The RAON CLS system consists of a beam merging section, CEC & Doppler tuning section, Detection section, and off-line ion source (OLIS) section. It has been manufactured and assembly is in progress by TRIUMF, Canada. Since the resonance frequency is different depending on the type of ion beam used in the experiment, it is necessary to be able to generate lasers of various wavelengths. For this purpose, two dye laser (565˜610, 610˜665 nm) and Ti:Sa laser (670˜1050 nm) systems that are tunable laser systems were constructed. For shorter than 570 nm wavelength laser generation, a frequency doubler that can operate in the 500-700 nm (285˜330 nm generate) region was constructed. Currently, an optics set of frequency doubler that can operate in the 670-1050 nm (335˜525 nm generate) region is being prepared.

We plan to complete the installation of the RAON CLS system by the end of 2022, generate an Al ion beam using OLIS, and conduct the CLS experiments of Al ion beam to complete the commissioning of the RAON CLS system.

PS-7-8

Laser Resonance Chromatography

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Optical spectroscopy of superheavy elements is experimentally challenging as their production yields are low, half-lives are very short, and their atomic structure is barely known. Conventional spectroscopy techniques such as fluorescence spectroscopy are no longer suitable since they lack the sensitivity required in the superheavy element research. A new technique called Laser Resonance Chromatography (LRC) could provide sufficient sensitivity to study super-heavy ions and overcome difficulties associated with other methods. In this contribution, I will introduce the LRC technique and describe the result of the first LRC test experiments. This work is supported by the European Research Council (ERC) (Grant Agreement No. 819957).

Development of a laser lab for collinear (and resonance ionization) laser spectroscopy

PS-7-9

Shujing Wang[1], Xiaofei Yang[1], Shiwei Bai [1], Yunkai Zhang [1], Yongchao Liu [1], Hanrui Hu [1], Guilin Mao [1], Peng Zhang [1], Zeyu Du [1], Yangfan Guo [1], Qite Li [1], Yinshen Liu [1], Zhou Yan [1], Yanlin Ye [1]

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Collinear laser spectroscopy (CLS) method can nuclear-model-independently measure basic properties of nuclei, such as nuclear spins, magnetic moments, quadrupole moments and charge radii by probing the hyperfine structure and isotope shifts [1]. Measuring the hyperfine structure spectrum using CLS is mainly based on two approaches: laser-induced fluorescence (LIF) and resonance ionization spectroscopy (RIS), which requires the use of single narrow-band continuous wave (cw) laser beam and multiple pulse laser beams, respectively.

Based on LIF approaches, our group has developed and demonstrated a collinear laser spectroscopy setup for the study of the unstable nuclei at the radioactive ion beam facility in China [2-3]. Currently, the development of the collinear resonance ionization spectroscopy using the RIS approach is also on-going. To satisfy the needs of CLS measurement using both LIF and RIS approaches, we have developed a laser lab, including narrow-band cw laser and its frequency-doubling, narrow-band pulsed laser and its 2nd/3rd/4th harmonic generation, broad-band pulsed laser and its 2nd/3rd/4th harmonic generation, high-power YAG lasers, as well as the frequency-stabilization and calibration system. Excepting the commercial lasers which need to be installed and tested, a home-made injection-locked cavity [4] and its 2nd/3rd/4th harmonic generation to produce narrow-band pulsed laser are developed. The laser system has been successfully applied to the high-resolution CLS measurements [2-3] using both LIF and RIS approaches.

In this presentation, the details of the laser system and its application on the laser spectroscopy experiments will be presented, as well as the on-going plans for the RIS scheme test of stable isotopes.

PS-7-10

Recent upgrade and development at TRIUMF's polarizer facility

Ruohong Li[1], Jens Lassen [1], C. D. Philip Levy [1], Gerald D. Morris [1], Alexander Gottberg [1]

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Using collinear optical pumping technique, the laser-nuclear-spin-polarization beam facility at TRIUMF-ISAC, operating since 2002, routinely provides nuclear-spin polarized radioactive isotope beams, such as ^{8}Li and ^{31}Mg, for beta detected nuclear magnetic resonance studies in material science, biochemistry, nuclear physics, and fundamental symmetries. To meet the increasing demands from emerging research of beta-NMR in biomedical physics and material science and to laser polarize isotopes, such as Ac and Cu, an upgrade of our laser and beamline systems is underway. An overview of the present polarizer facility will be given, and recent upgrades and ongoing development work will be discussed.

Optimization of the collinear laser spectroscopy beamline and Test on stable isotopes

PS-7-11

P. Zhang[1], X. F. Yang[1], S. W. Bai[1], S. J. Wang[1], Y. C. Liu[2], Y. S. Liu[1], H. R. Hu[1], Y. F. Guo[1], Z. Yan[1], Z. Y. Du[1], W. C. Mei[1], Y. K. Zhang[1], X. Y. Fu[1], Q. T. Li[1], Y. L. Ye[1]

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Collinear laser spectroscopy (CLS) is a well-established tool to measure the fundamental properties of atomic nuclei simultaneously in a nuclear-model independent way [1]. It probes the hyperfine structure (HFS) and isotope shift arising from the interaction between nucleus and surrounding electrons to obtain nuclear spins, magnetic dipole moments, electric quadrupole moments and mean-square charge radii [2]. To study the unstable nuclei at the radioactive ion-beam facilities in China, our group has developed a collinear laser spectroscopy apparatus based on laser-induced fluorescence (LIF) approach, which has been tested with stable beam[3] and successfully applied at the BRIF RIB facility[4,5].

Further optimization and test of the in-house CLS system have been continuously performed using stable ion beams from the laser ablation ion source the off-line CLS system, such as the rotational lens system for the control of the ablation laser spot, beam spot diagnostics using phosphor screens, the real-time monitoring of the beam intensity, calibration of the neutralization efficiency and so on. In addition, extension of the current CLS system into the high-sensitivity collinear resonance ionization spectroscopy is ongoing.

In this presentation, details on the optimization and test of the CLS based on stable ion beams will be discussed, together with the progress on the of the development of the collinear resonance ionization spectroscopy setup.

PS-7-12

GPIB & PIPERADE apparatus for the new DESIR hall at GANIL

Audric Husson[1], Mathias Gerbaux [2], Pauline Ascher [3], Bertram Blank [4], Laurent Daudin [4], Marjut Hukkanen [5], Antoine de Roubin [6], Benoit Lachacinski [4], Mathieu Flayol [3], Phillipe Alfaurt [4], Stéphane Grévy [3], Sean Pérard [3]

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The DESIR (Désintégration, Excitation et Stockage d'Ions Radioactifs) hall is a part of the new SPIRAL2 facility under construction at GANIL. This hall will be dedicated to the study of nuclear physics at low energy (30-60 keV). Dedicated projects have been proposed and are under construction to study the available rare isotopes, which are of particular interest for nuclear structure, nuclear astrophysics, fundamental interactions and applications.

DESIR experiments will benefit from radioactive ion beams from both SPIRAL1 and SPIRAL2 facilities. Several key regions of the nuclear chart will be accessed through various production mechanism: light exotic nuclei via fragmentation production from the historical SPIRAL1 facility, or neutron deficient and heavy elements beyond uranium from the new SPIRAL2/S3 complex. However, these production methods are non-selective, limiting the purity of the beams of interest and consequently high precision measurements as required for nuclear structure studies. In order to ensure the cleaning and purification as well as the bunching and cooling of the RI beams through DESIR, three devices are under commissioning at the LP2i Bordeaux among which a High Resolution Separator (HRS), a RFQ cooler-Buncher (GPIB) and a double Penning trap (PIPERADE).

Using the same mechanical design as ISCOOL at CERN, the GPIB (General Purpose Ion Buncher) is a radiofrequency quadrupole cooler-buncher. The GPIB aims at reducing the emittance of the RI beams from 80π mm.rad down to 3π mm.rad at 60 keV and bunch the beams on request from the DESIR hall experiments. The RF circuit of the GPIB has been designed to accept masses from m=5u to m=250u and to support RF potentials higher than 4 kV peak to peak. Such high RF power will benefit to DESIR in cooling and bunching ion pulses up to 10^8 ions per bunch. Currently under commissioning, transmission of more than 90% and significant decrease in transverse emittance have already been measured for CW beams.

On its side, PIPERADE is a double-Penning trap, designed either to measure the mass of radionuclides by itself or to deliver large and very pure samples of exotic nuclei to the different experiments in DESIR. PIPERADE show a large inner diameter for the first trap that will mitigate space charge effects. Purification cycles will be performed over milliseconds to separate short-lived nuclei and to extract the ions of interest from the large amount of isobaric contaminants. These latter will be accumulated into the second trap until they constitute a sufficiently pure sample for the measurements. The mass resolving power of PIPERADE is expected to be higher than 10^5 in the case of gas-free measurement techniques (ToF-ICR or PI-ICR) and will allow purification of close isobars and even isomers. Using the TOF-ICR as well as the new PI-ICR techniques, mass precision of 10^{-8} will be reachable for short-lived nuclei.

The combined use of the HRS, the GPIB and PIPERADE will ensure high quality ion samples to all the DESIR experiments. The GPIB and PIPERADE are now fully assembled at LP2i Bordeaux and under commissioning before their transfer to GANIL in 2 or 3 years. Their status will be presented as well as the recent achievements.

PS-7-13

Ion trapping properties of SCRIT: Time evolution of charge state distributions of ^{138}Ba ions

Akitomo Enokizono[1], Ryo Ogawara[2], Hikari Wauke[3], Kazuyoshi Kurita[1], Kyo Tsukada[4], Masahiro Hara[5], Masamitsu Watanabe[5], Masanori Wakasugi[6], Shinichi Ichikawa[5], Tetsuya Ohnishi[5], Toshimi Suda[7], Toshitada Hori[5], Yasushi Abe[5], Yasushi Maehara[2]

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The SCRIT (Self-Confinement RI ion Target) technique [1] is an internal target formation technique that achieves electron scattering off unstable nuclei produced from the ERIS (Electron-beam-driven RI separator for SCRIT) [2].
The target ions incident from the outside of the SCRIT are trapped transversely by the periodic focusing force of the electron beam and longitudinally by the well-type electrostatic potential.

While the target ions are trapped in the SCRIT, the ion trapping properties (number of trapped ions N_{trap}, average charge state q_{ave}, etc.) continue to change. To evaluate the ion trapping properties, the SCRIT system is equipped with an ion analyzer consisting of the total charge monitor that measures $N_{trap}{\times}q_{ave}$, the ExB filter (wien filter) that separates the mass-to-charge ratio of the trapped ions, and a 43-channeltron array [3]. The luminosity is monitored with a Bremsstrahlung-gamma ray detector. If the number of trapped ions in a highly charged state increases (trapping time > 50 ms), q_{ave} is required to evaluate N_{trap}. Therefore, in order to evaluate the correct SCRIT performance with trapping time of > 50 ms, we investigated the time evolution of the charge state distribution for trapping times of 30 - 500 ms using ^{138}Ba ions.

The results show that the trapping time to effectively utilize the trapped ^{138}Ba ions for the electron scattering was about 200 ms.
In the trapping time of 200 ms, the luminosity was achieved $1.6{\times}10^{27}$ [$\mathrm{cm^{-2}s^{-1}}$] at Ninj of $3.6{\times}10^{8}$, and the Ntrap was $7{\times}10^{7}$ and the average charge state of ^{138}Ba ions was 4.0. The ion trapping properties of SCRIT strongly depend on the emittance of the incident target ion beam and the electron beam conditions. Therefore, these evaluations are very important for optimizing the experimental conditions of the SCRIT.

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The Phase Imaging Ion Cyclotron Resonance Technique for High Precision Mass Measurements of Short-Lived Exotic Nuclei

PS-7-14

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With the Facility for Rare Isotope Beams (FRIB) beginning operation at Michigan State University (MSU), new and improved instrumentation and techniques are necessary in order to measure the properties of increasingly short lived, low-production rate nuclei. One commonly sought after property for almost all nuclear physics applications is the nuclear mass. Penning Trap Mass Spectrometry (PTMS) has long been the gold-standard for precision mass measurements; at FRIB, the Low Energy Beam and Ion Trap (LEBIT) [1] will continue to perform measurements of rare isotopes using PTMS, addressing science topics of interest to the nuclear physics community.

This year, LEBIT successfully implemented the Phase-Imaging Ion-Cyclotron-Resonance (PI-ICR) technique originally developed at the SHIPTRAP Penning trap by Eliseev et al. This technique provides a 25-fold improvement in precision, and 40-fold increase in resolving power over the traditional Time-Of-Flight Ion-Cyclotron-Resonance PTMS technique [2]. The method works by projecting ions in a Penning trap onto a high-resolution position-sensitive microchannel plate (MCP) detector and determining the mass-dependent frequency ions were oscillating at by measuring their phase before and after a precisely set phase accumulation time. In addition to implementing the standard ion-excitation scheme used for PI-ICR by the other PTMS groups, LEBIT has utilized Lorentz-steerers [3]—which allow for control of initial ion location in the Penning trap—in order to develop a new ion-excitation scheme. This novel scheme would eliminate some common systematic errors associated with some PI-ICR setups and allow for LEBIT to be able to trust the result of a single mass measurement instead of being forced to fit measurements made over multiple systematically varied phase-accumulation times. The ability to seamlessly switch between three different detection schemes, TOF-ICR, FT-ICR [4], and PI-ICR, ensures that LEBIT will be able to optimize the opportunities for science that the new FRIB facility will make available.

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PS-7-15

Saturated absorption spectroscopy using the Ti:Sa laser for RAON CLS

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Collinear Laser Spectroscopy (CLS) has been used to investigate basic nuclear properties such as nuclear spin, electromagnetic moment, and mean-square charge radii for the radioctive isotopes produced by accelerator facilities.

For the RAON CLS experiment, tunable lasers essential to study various atom currently, are prepared, which are dye laser and Ti:Sa laser and their second harmonics repectively. In this report, using one of these, Ti:Sa laser, the spectrum of D1 and D2 lines of 85Rb, 87Rb, and 137Cs atoms were obtained by saturation absorption spectroscopy, which is one of the high-resolution spectroscopic techniques. For CLS, the laser frequency line width should be narrow and the laser should be stable at a specific frequency for a long time. Therefore, the frequency stability was measured using the spectral signal.

In addition, a detailed analysis was performed on the power broadening that should be considered in the interaction between atoms and lasers. The measured hyperfine structure will be compared with ab-inito calculation using relativistic atomic structure code, multi-configuration Dirac-Fock .

Preliminary beam experiment results of single bunch selection at RAON facility

PS-8-1

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To enable neutron time-of-flight (TOF) experiments at the RAON heavy-ion accelerator facility, we tested a single bunch beam selection method by combining a fast chopper and double gap buncher in the low-energy beam transport (LEBT) section. The fast chopper converts a CW beam into hundreds of nanoseconds pulsed beam. Then, the double gap buncher performs bunching to shorten the pulse length to less than one radio frequency quadrupole (RFQ) cycle. Ideally, a single isolated bunch can be achieved after the RFQ. In this study, we discuss design of single bunch selection system and preliminary beam experiment results.

PS-8-2

Development of ultra-fast plastic scintillation counter with reaching time resolution around 5 ps

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The measurement of the time of flight(TOF) of charged particles can give important information for particle identification through the determination of particle velocity. In order to improve the resolution of particle identification, it is effective to improve the time resolution of the scintillation counters for TOF measurements.

In the present study, we developed a plastic scintillation counter with an extremely good time resolution by combining a fast plastic scintillator and new high-speed photomultiplier tubes. Recently, HAMAMATSU PHOTONICS K.K. developed a new type series of ultra high-speed photomultiplier tube that places the anode potential near the first dynode. On the other hand, ELIJEN TECHNOLOGY also developed ultra-fast scintillators by adding trace amounts of benzophenone as a quenching agent. We assembled the detector by mounting two PMTs of this series on either side of the ultra-fast scintillator of rectangular shape. In order to test the performance of these detectors, we measured the time resolution using primary beams such as ^{132}Xe at 420 AMeV at the HIMAC synchrotron accelerator facility at National Institutes for Quantum Science and Technology. We investigated the dependence of time resolution on scintillator size and thickness, the high voltage applied to the PMT, the type of PMT, and the threshold level of the discriminator, and searched for the conditions with the best time resolution. As a result, a time resolution of around 5 ps was obtained as a preliminary value. In this presentation, we will present the final results of the study.

Development of large GAGG:Ce calorimeter for measurements of the cluster knockout reactions

PS-8-3

Ryotaro Tsuji[1], Junki Tanaka [2], Koshi Higuchi , Yuto Hijikata [3], Shoichiro Kawase [4], Riku Matsumura [5], Tomohiro Uesaka [6], Hiroyuki Takahashi [7], Juzo Zenihiro [3], Kanta Yahiro [3], EiIchi Takada [8], Hideaki Otsu [2]

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We have launched the "ONOKORO" project to understand cluster formation phenomena in nuclei and nuclear matter from measurements of the cluster knockout reactions ((p,pX) reactions(X=d, t, ^{3}He, α)).

In order to measure the reactions using inverse-kinematics, we have developed the "TOGAXSI" telescope consisting of Si trackers and large GAGG:Ce calorimeters. The required performance of the calorimeter is high energy resolution(~1A MeV (rms)) under the high count rate (~100 kcps) and wide energy range (100A-250A MeV).Therefore, we have developed new calorimeter using large GAGG:Ce crystal(35 mm × 35 mm × 120 mm) which is high resolution(8~9 % (662 keV, FWHM)), high density (~6.63 g/cm^3) and fast response(decay time~90 ns).

In this presentation, we report recent results of the performance test with proton and α beam at HIMAC, QST.

PS-8-4

Development of Silicon strip detector for cluster knockout reactions

Koshi Higuchi[1], Hidetada Baba [2], Hiroyuki Takahashi [3], Junki Tanaka [4], Juzo Zenihiro [5], Kanta Yahiro [5], Riku Matsumura [1], Ryotaro Tsuji [6], Shoichiro Kawase [7], Shoko Takeshige [8], Shunsuke Kurosawa [9], Tomohiro Uesaka [2], Yuto Hijikata [5]

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The ONOKORO project has been launched to understand what kind of clusters exist in the atomic nucleus, and how the formation of the clusters changes depending on the neutron richness. The cluster knockout reactions in inverse kinematics are to be performed using heavy nuclear beams. A detector array TOGAXSI is going to be constructed to measure 100-230 MeV/u light ions emitted from the reactions. In the presentation, the silicon strip detector composing TOGAXSI will be introduced. A performance evaluation experiment of the silicon detectors with a thickness of 100 μm and strip width of 100 μm was performed. The energy losses of light ions are key observables to identify the type of knocked-out clusters. The energy loss spectra with proton beams and alpha particle beams were obtained. In particular, the 230 MeV/u proton beam gives 58 keV at the peak value of the Landau distribution, and its spectrum starts from about 40 keV. The low noise condition has been achieved using APV25s1 chips, and succeeded in measuring them with good detection efficiency.

Detector array "TOGAXSI" for inverse-kinematics clusters and nucleon knock-out reaction experiments

PS-8-5

Junki Tanaka[1], Tomohiro Uesaka [2], Juzo Zenihiro [3], Hidetada Baba [2], Koshi Higuchi , Yuto Hijikata [3], Shoko Takeshige [4], Ryotaro Tsuji [5], Shunsuke Kurosawa [6], Kanta Yahiro [3]

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We have started a new research project named the "ONOKORO" project. The project comprehensively investigates clustering in medium-to-heavy mass nuclei with cluster knock-out reactions at the intermediate-energy facilities. "TOGAXSI" is the name of the new detector array. It measures scattering angles and the energies of d, t, 3He, and α emitted at 6-30 degrees in the laboratory system and accompanied recoil protons with angular and energy resolution of ˜ 3 mrad and ˜1 MeV, respectively. The telescope consists of 100-μm-thick, 100-μm-pitch silicon strip detectors, and GAGG(Ce) scintillation detectors.

In the presentation, we introduce the TOGAXSI array and report the present status of the detector constructions.

PS-8-6

Development status of the detector system for IF separator at RAON

Eunhee Kim[1], Yong Hwan Kim [1], Jang Youl Kim [1], Chong Cheoul Yun [1], Hyun Man Jang [1]

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In-flight fragment (IF) separator at RAON aims to generate various rare isotopes and separate isotope beams of interest. Detector system for beam particle identification at the separator has been developed based on TOF-Bρ-ΔE method. Parallel plate avalanche counters (PPACs), plastic scintillators, and silicon detectors will be used to measure the position, timing and energy-loss of the isotopes produced by the separator. IF detectors and data acquisition (DAQ) system are currently being installed at the focal planes of IF separator. Details on the development status of detector and readout systems of IF separator will be discussed in the presentation.

Study on the application of SiPM to γ-ray and charged particle measurement using scintillation crystals

PS-8-7

Sunghan Bae[1], Sunghoon(Tony) Ahn[1], Soomi Cha[1], Jongwon Hwang[1], Dahee Kim[1], Yunghee Kim[1], Chaeyeon PARK[2], Kevin Insik Hahn[1]

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Silicon Photo Multiplier (SiPM) is a light sensor which has multi micro pixels working in Geiger mode with several tens of volts. The SiPM has been recognized as an alternative to the Photo Multiplier Tube (PMT) for its compact size of millimeter order and its robustness to magnetic field. The signals from SiPM are proportional to the number of fired pixels, not directly to the number of incident photons and they can be different from those of PMT. Recently, the SiPM-based scintillation detectors are actively studied for various purposes including energy calorimetry [1, 2], time of flight measurement [3] and imaging for medical scan [4 - 8]. Their performance showed large variance implying the versatility of such detector systems. Thus, it is crucial to find an optimized application of SiPM for each detector system.

The purpose of our study is to develope SiPM-based scintillation detector system for γ-ray and charged particle measurement. We have inspected the performance of the SiPM attached on CsI(Tl) and GAGG(Ce) crystals by applying radiation sources. The energy resolution and gain depending on the over voltage are identified with single SiPM on the crystals, and we identified improved energy resolutions using multiple SiPMs under the optimized over voltage. Furthermore, the position dependence of energy spectra from separated SiPMs on single bulk crystal is noticed, and a possible way to merge separated signals from multiple SiPM on a bulk scintillator without relative gain matching is demonstrated. We will present these results and future applications of the SiPM-based scintillation detector system for nuclear physics experiments.

PS-8-8

Novel detector systems for decay spectroscopy at FAIR/NUSTAR

Juergen Gerl

Recently, the combination of the highly pixelated active DSSSD AIDA implanter and the compact, high-efficiency Ge array DEGAS-I has been commissioned and employed for first successful NUSTAR experiments at FAIR Phase-0. Based on the experience gained, a novel type of implanter, FIMP, aiming for highest efficiency, low-noise and ultimate timing characteristics is under development. For the first time, FIMP will be employing scintillating fibres. It will perfectly match to the future variants of the gamma array DEGAS-II and DEGAS-III. The latter one planned to be the first imaging grade gamma spectrometer, enabling the event-by-event distinction of gamma quanta emitted from the implantation zone versus quanta originating from the strong environmental background. The sensitivity gain of this set-up is estimated to be orders of magnitude, compared to conventional ones.

Performance comparison of various electronics systems for fast-timing measurements using the KHALA LaBr3(Ce) detector array

PS-8-9

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Precise lifetimes of excited nuclear states are essential information to understand the nuclear structure. For example, the nuclear quadrupole deformation can be reduced from the E2 transition probabilities of the nuclei. In these days LaBr3(Ce) crystals are commonly adopted to measure the lifetimes of excited states down to tens of picoseconds because of their prompt timing response and good energy resolution.

To facilitate the precise lifetime measurement in studying the nuclear structure the Center for Extreme Nuclear Matters (CENuM) has developed the Korea High-resolution Array with LaBr3(Ce) (KHALA) for the three years. KHALA that consists of total 36 LaBr3(Ce) crystals read out by photomultipliers were assembled and tested with the radiation sources. Recently, as the joint effort between KHALA and FATIMA in Europe, the IDATEN (International Detector Assembly for fast-timing measurement of Exotic Nuclei) Collaboration was formed for the biggest ever LaBr3(Ce) system for nuclear physics. The campaign experiment using IDATEN system is being planned at RIBF, RIKEN, using total 84 LaBr3(Ce) crystals, in near future.

At present the data acquisition system for KHALA and IDATEN is being investigated. Currently, three options for the electronics systems, employing different working principles, are available: the digitizers with Constant-Fraction Discriminator (CFD), the traditional analog electronics, and the Time-to-Digital Converter (TDC) based system. The benchmark tests using the radioactive sources have been performed for all three systems with (1) the commercially available CAEN digitizers, (2) the analog electronics composed of ORTEC CFD and the TAC module and (3) the Twin-peak TAMEX which is the newly developed electronics system by GSI. In this presentation, we summarize the results of the benchmark tests with three options for energy resolution, time resolution, prompt response curve, and the electronics effect caused by jittering and the clock dependent biases. This effort enables us to compare the advantages and disadvantages of the three electronics systems, reaching the final selection for KHALA and IDATEN.

PS-8-10

Development of a fast response PPAC for high-intensity heavy-ion beams

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Parallel Plate Avalanche Counter (PPAC) is generally used as beam-line detectors for position measurements in RI beam facilities. A delay-line PPAC, a conventional type of PPAC deduces the position of particles using the time difference of signals from both ends of electrodes connecting a delay line. However, there is a limit on the counting rates due to the multi-hitting within the delay time. We have developed a Strip-Readout PPAC (SR-PPAC) with two cathode planes for positions X and Y with strip electrodes. By separately reading out from each electrode detection efficiency has been achieved near 100 % even for high-intensity beams much more than 10^5 cps.

We have tested SR-PPAC in accelerator facilities and evaluated the detection efficiency and the position resolution. The detection efficiency was more than 99% even for a 700 kHz RI beam and the position resolution achieved about 300 μm(FWHM), which is comparable to Multi-Wire Drift Chamber.

Development of the STARK detector for nuclear reaction studies

PS-8-11

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Single-nucleon transfer reaction in inverse kinematics with radioactive beams is one of the powerful methods to study nuclear astrophysics, nuclear reaction, and other applications. Since outcoming particles from the transfer reaction carry important nuclear spectroscopic information, an accurate detection system for charged particles is required to measure their energies and angles. A silicon detector array providing a large solid angle coverage with good energy and position resolution has been developed and used for such measurement [1,2].

Silicon Telescope Array for Reaction studies in inverse Kinematics, STARK, is under development at the Center for Exotic Nuclear Studies to perform nuclear reaction experiments including elastic scattering and neutron transfer reaction. The array is composed of 3 rings to cover a large angular range and consists of 40 double-sided, resistive silicon strip detectors and 12 single-sided, non-resistive strip detectors. The expected angle resolution is less than 1°, and the angle coverage is 43~78° and 105~150°. The GET (General Electronics for Time projection chamber project) electronics system is used to handle about 1000 channels from detectors. Several elastic scattering experiments are considered as commissioning of the STARK at the KoBRA in the early stage of RAON. Current status of development and a detailed description of the detector system will be presented.

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PS-8-12

RFQ Developments at the CERN-ISOLDE Offline 2 mass separator

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The Offline 2 mass separator laboratory is part of the CERN-ISOLDE Offline facilities - a suite of installations required to perform essential quality control on target and ion source units before irradiation at CERN-ISOLDE. The facility is also used for extended preparatory offline studies as a prerequisite before conducting any beam development on-line, especially establishing systematic effects. The Offline 2 separator resembles the online CERN-ISOLDE Frontend and employs identical services such as beam instrumentation, gas delivery system, laser ionization and the equipment control system. The facility is able to generate dc as well as bunched non-radioactive beams up to an energy of 60 keV. The mass resolving power of the existing 90° dipole mass separator magnet is R≈500. The ion beams can be cooled and bunched in an unmodulated RFQ. In order to study effects of the RFQ buffer gas on the formation of molecular species, a dedicated identification setup is required. We intend to employ a Wienfilter after the RFQ. This work presents initial beam dynamics simulations through the RFQ and the mass filter. The simulations are based on 3D RF-fields. Furthermore, we present the ongoing installation of a Magnetof ion detector and an emittance meter in front of and behind the RFQ, respectively. Finally, the beam measurements as time resolved ion counts as well as the emittance will be compared with the simulations.

Technique of decay correlated mass measurement via multi-reflection time-of-flight mass spectrograph with an α/β-TOF detector

PS-8-13

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The atomic masses are most fundamental physical quantity and is the indicator that determines its existence and stability of nuclides. Comprehensive mass measurements provide us with important information to enhance our knowledge of physics in extreme regions, such as the astronomical r-process and the origin of Uranium.

The multi-reflection time-of-flight mass spectrograph (MRTOF-MS)[1] is one of the mass measurement device for the heavy elements. Recently a state-of-the-art detector referred to as an α-TOF[2] has been developed and installed to MRTOF-MS. The α-TOF detector can measure ion implantation to deduce the time-of-flight (TOF) and subsequent α-decay and fission (spontaneous fission (SF), β-delayed fission, etc.) events from implanted ions simultaneously, which can discriminate "true" events from background events. We have recently succeeded in the direct mass measurement of the superheavy nuclides ^{257}Db[3], which had a count rate of about two events per day.

Furthermore, we have initiated the new field of nuclear spectroscopy using the decay-correlated mass measurement[4]. This value of the technique was initially demonstrated by using the decay properties to discriminate and mass analyze the isomeric state of nuclides, which could not be resolved from the ground state using the TOF spectrum of MRTOF. Recently we have developed β-TOF[5], an improved version of α-TOF, and extended its measurement areas to include β-decaying nuclides. In this talk, we will introduce the technique of the decay correlated mass measurement using MRTOF and α/β-TOF.

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PS-8-14

Nitrogen gas scintillation counter for highly-intense heavy ion beams with negligible radiation damage

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Experiments using RI beams often require identification of the nuclides. In case of projectile-fragment separator, the identification is performed by measuring time-of-flight, energy loss, and magnetic rigidity. Radiation damage to these detectors has become a problem due to the highly intense heavy ion beams. We have solved this problem by developing a nitrogen gas scintillation counter in which radiation damage can be ignored by flowing the nitrogen gas continuously.
The detector is designed to install at the focal plane of the BigRIPS in RIKEN. The sensitive volume of 50 cm x 50 cm x 100 cm is filled with N2 gas at a pressure of 1 atm. The effective area is 60 mm in diameter. The photons are detected with PMTs, which are connected to both sides of the sensitive volume. The detection is easy since the main emission wavelength is 300-400 nm. The detection efficiency is sufficient for heavy RI beams even though the number of photons is less than that produced in noble gases. The short decay time constant at each wavelength makes it possible to use the counter as a time-of-flight counter for a highly intense beam.

In this presentation, we will report (1) the scintillation light yield in the detector measured with a 241Am source, (2) the intrinsic time resolution measured at CYRIC, Tohoku University, and (3) particle identification of 132Sn at RIBF.

Transfer reaction measurements using SNACK at KoBRA PS-8-15

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KoBRA (KOrea Broad acceptance Recoil spectrometer and Apparatus) [1] will produce RI beams with energies of 5 to 10 MeV/u from stable ion beams (10 ~ 40 MeV/u) delivered from the superconducting linear accelerator SLC3 of RAON (Rare isotope Accelerator complex for ON-line experiments) [2]. In its early phase of operation, transfer reaction measurements with these RI beams can be performed for nuclear astrophysics studies.

SNACK (Silicon detector array for Nuclear Astrophysics study at KoBRA) has been developed at RISP (Rare Isotope Science Project) in order to measure the light ejectiles from the transfer reactions. With the beam trajectories obtained from upstream PPACs (Parallel Plate Avalanche Counter), excitation energy levels in the heavy recoils can be reconstructed by measuring light ejectile's energies and scattering angles. The expected results of transfer reaction measurements with SNACK and KoBRA beamline detectors were calculated by using a Monte Carlo simulation. This talk with present details of the detector development and simulation results.

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PS-8-16

High-precision MRTOF mass measurements of radioactive isotopes at RIKEN's RIBF facility: Recent projects for ion selection, wideband mass accuracy, and mirror potentials

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During the last decade, the multi-reflection time-of-flight mass spectrograph (MRTOF-MS) [1] became a powerful device for precise mass measurements of short-lived isotopes. Exotic ions produced at radioisotope facilities are stored in an electrostatic ion trap with nearly closed-path trajectories at kinetic energies on the order of a few keV, *i.e.* the ions are reflected back and forth between two electrostatic ion mirrors, and ultimately ejected to a detector for time-of-flight determination. The growing popularity of these spectrometers is mainly due to the short measurement duration of typically $t < 50\,\mathrm{ms}$, a high mass resolving power (typically $R_m > 100,000$), and a mass measurement precision reaching $\delta m/m < 10^{-7}$.

At the new MRTOF-MS setup located downstream of the BigRIPS separator and ZeroDegree spectrometer at RIBF/RIKEN [2,3], efforts have been made to improve the overall performance of state-of-the-art MRTOF technology. The resolving power of the system has been optimized using a pulsed drift tube outside of the MRTOF-MS to obtain a useful overview of the ions' TOF-energy dispersion. Combined with subsequent fine tuning, a remarkable resolving power of $R_m > 10^6$ has been achieved, which allows for resolution of low-lying nuclear isomers. Furthermore, a new in-MRTOF deflector [4] has been installed with the ability to transmit one or several chosen ion species at the same time, while deflecting all other ion species. To this end, a pre-calculated pulse pattern is used, which guarantees for an undisturbed transport of the ions of interest. In order to tackle the accuracy challenge for large mass differences between the ions of interest and the ions used as a mass reference, new efforts have been made. By identification and elimination of non electrostatic contributions to the ions' time-of-flight, we aim to solve long-standing difficulties for the mass accuracy achieved in wideband MRTOF mass measurements. The presently known causes of uncertainties and our approaches will be discussed.

As a new development, a campaign for studying electrostatic mirror potential distributions is now being performed based on simulations (in one and in three dimensions) with the goal to fully replace the presently used field distribution, and to enable targeting at any wanted TOF-energy dispersion required for a high mass resolving power. An approximately isochronous transport covering a range of as much as 1 keV of kinetic energies is anticipated. The applied method and first results of this study will be presented as an outlook to future operation.

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PS-8-17

Extending the reach of the mass spectrometer SHIPTRAP towards superheavy elements

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The ultimate boundary of existence of chemical elements remains an open question. The heaviest elements known to date, called Superheavy Elements (SHEs, with $Z > 103$), owe their existence to the stabilizing effect of nuclear shells, which counteracts the strong Coulomb repulsion that would otherwise cause their immediate fission. The SHIPTRAP mass spectrometer, placed behind the SHIP separator at GSI (Darmstadt, Germany), has been used to measure the masses of several isotopes of elements up to dubnium and, through these, to study the evolution of the shell gaps in the region around $Z = 100$ and $N = 152$. Thanks to mass resolving powers of over 10^7 it was also possible to resolve and to characterize several low-lying long-lived isomeric states. Lighter nuclides were studied as well, allowing, for example, the identification of a predicted isomer in californium-241 and the study of the alpha-decay chains stemming from francium-206 and 204, where some previously uncertain isomeric excitation energies have been determined.

The shell-structure investigations of the heaviest nuclides can be complemented by mass measurements of long-lived actinide isotopes. Recently, uranium and plutonium isotopes obtained by laser ablation from drop-on-demand targets have been studied. These measurements included a detailed study of systematic uncertainties in mass measurements for cases with large mass-to-charge ratio differences to the closest suitable reference ion. These problems could be circumvented if the actinide ions were available as doubly charged atomic ions. In that case, stable isotopes from tin or cesium, whose masses are well known, could be used as references.

In this contribution, the latest mass measurements obtained at SHIPTRAP will be presented. In addition, the long-term efficiency of the setup will be addressed. This is fundamental for the study of even heavier nuclei, produced with lowest rates. Furthermore, the development of a compact gas cell to extract doubly-charged actinides (emitted from a radioactive recoil source placed inside the active gas volume) will be introduced.

PS-8-18

Simulation and Determination of the absolute neutron detection efficiency in large neutron detectors

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While neutrons emitted in intermediate heavy-ion collisions are essential to understand the properties of the strongly interacting baryonic matter, detection of neutrons and simulations of neutron detector performance and efficiencies are difficult. We have developed a SCINFUL-GEANT4 based on the reaction channels and cross-sections in the SCINFUL-QMD simulation code [1] which has a fixed cylindrical detector backed by one photo-multiplier. The fixed geometry in SCINFUL-QMD limits its use to non-cylindrical shaped detectors especially detectors with two or more photo-multipliers. By implementing the GEANT4 toolkit into SCINFUL-GEANT4, the new code can be applied to a variety of the detector geometries, including the Large Area Neutron Array (LANA) in and the Facility for the Rare Isotope Beams (FRIB), U.S.A. used to measure neutron emitted in heavy ion collisions. LANA consists of two walls. Each 2x2 m^2 wall has 25 rectangular pyrex bars stacked on top of each other. Each bar is a 2 meter long with a cross-sectional area of 7.62x6.35 cm^2 filled with NE-213 liquid scintillator. The Pyrex is 3 mm thick.

LANA has been used successfully in several heavy ion experiments at the National Superconducting Cyclotron Laboratory (NSCL) that measured both neutrons and charged particles in an effort to understand the symmetry energy term in the nuclear equation of state. Neutron spectra have been generated from the collisions of $^{40,48}Ca$ beams on $^{58,64}Ni$ and $^{112,124}Sn$ targets. To understand the properties of nuclear forces that depend on neutron-to-proton imbalance, the proton and neutron spectra obtained from reactions formed by different combinations of the projectile and targets will be compared. While proton detection with Si detectors is near 100% efficient, neutron detection is often less than 10% and requires accurate detection efficiency corrections. Comparison of the simulation results from SCINFUL-GEANT4 to the NSCL data including closure tests to verify our estimation about the neutron detection efficiencies of LANA will be discussed at the presentation.

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‘Finding a needle in a haystack;’ A Ba-tagging approach for an upgraded nEXO experiment

PS-8-19

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nEXO is a proposed 5-tonne experiment that will search for neutrinoless double-beta decay (0SSSS) in 5-tonnes of liquid xenon (LXe), isotopically enriched in Xe-136. If observed, 0SSSS will violate the assumed symmetry of lepton number conservation in the Standard Model.

Complete position localization of events in the nEXO time projection chamber opens the possibility of extracting from the detector volume and identifying the Xe-136 0SSSS decay daughter Ba-136. This is called Ba-tagging, a technique being developed as a potential future upgrade for nEXO. The approach pursued by collaborating Canadian institutions involves the extraction of a small volume of LXe from the site of a potential 0SSSS event using a capillary and deploying a combination of RF (Radio Frequency) ion transport and spectrometry techniques to identify single Ba-136 ions.

With an RF-only ion funnel, the extraction of Cf-252 fission ions from xenon gas (up to several atm) to high-vacuum has been demonstrated. To positively identify the extracted ions, a linear Paul trap (LPT) and a multiple-reflection time-of-flight mass spectrometer (MRTOF-MS) are being commissioned. A quadrupole mass filter (QMF), located downstream of the RF funnel, filters incoming ions, which are subsequently cooled and trapped in the LPT to detect the barium ion through laser fluorescence spectroscopy. After element identification, the cooled ions are ejected into the MRTOF-MS to determine the ion masses and to perform systematic studies of the ion bunch. The commissioning and results of initial testing of these devices will be presented.

PS-8-20

A position-sensitive large-area microchannel plate detector with digital data acquisition system for studies of exotic nuclei

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We have developed and commissioned a position-sensitive large-area microchannel plate (MCP) detector with a new digital data acquisition system. The MCP detectors coupled to delay-line anodes are powerful tools for single particle/photon counting, by providing information on position and impact time of each particle/photon [1]. Therefore, MCP detectors are widely utilized in experimental setups for nuclear physics studies at low and medium energies.

Our new detector system consists of two large-area MCPs with 120 mm active diameter, mounted in chevron configuration, with delay-line (DL) anodes [2]. The digital-readout-based data acquisition system (DDAQ), which is coupled to the delay-lines of the detector, is based on a fast-timing amplifier unit and a CAEN v1751 FADC waveform digitizer (10-bit resolution, and 1 GS/s or 2 GS/s sampling rate) [3]. Our digiTES-based self-developed software manages the digital pulse processing, the intelligent triggering, and provides ADC, TDC, event timestamp and waveform data. The DL-MCP detector system will be exploited in the Rare-RI Ring setup at RIKEN for high-precision mass measurements [4,5], and in different future experimental setups at RAON for beam analytics and tracking of reaction residues [6].

In this talk, the details of our DL-MCP setup, properties of the detector and the programmed triggering method will be described, as well as the results of our commissioning with light charged particles. Additionally, the preliminary results of the measured position and time resolution will be discussed. The presentation will end with an outlook for experimental plans with our DL-MCP detector at RIKEN and RAON.

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Development of gaseous Xe scintillator for particle identification of high intensity and heavy ion beams

PS-8-21

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RIBF can provide very high-energy and high-intensity RI beams. However, the beam intensity is now limited due to the radiation damages and pile-up events of the particle identification (PID) detectors. Therefore, we are now developing a gaseous Xe scintillator, which is expected to have a better radiation hardness than the existing ones like plastic scintillators, ion chambers, and PPACs. It is also expected to have good energy resolution, timing, and position resolutions because Xe gas has good scintillation properties (small average energy per scintillation photon $\sim$ 20 eV and fast decay time constant $\sim$ 100 ns).

Recently, we have evaluated the PID performance (ΔE, timing and position resolution) of the gaseous Xe scintillator by using primary beams of ^{238}U and unstable nuclear beams at RIKEN RIBF. The results show that the gaseous Xe detector can be considered as a new beamline detector in all three aspects. In this presentation, we report the details of the experiment and the results.

PS-8-22

Constraints and characterization for use of in-beam diamond detectors in neutron-induced fission experiments

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Neutron-induced reactions on actinides are used to study the fission process and to populate neutron-rich isotopes for nuclear spectroscopy. Such studies often benefit from direct measurement of the emission time, mass and/or kinetic energy of fission fragments, thus requiring efficient detectors with good time- and energy resolution. In the case of in-beam operation of the fission fragment detectors with intense thermal neutron beams, additional constraints occur due to the beam-induced background and high radiation dose from neutron-induced reactions and the stopped fission fragments. Diamond detectors, which have fast timing response, good energy resolution and radiation hardness, are expected to satisfy these requirements and are anticipated to be used in such applications.

Diamond detectors of different type (single crystal or polycrystalline) and sizes from different manufacturers were characterized with the aim of developing innovative instrumentation for fission fragment detection applications. The detector characterization was carried out at the LOHENGRIN spectrometer at Institut Laue-Langevin with mass- and energy-separated fission fragment beams. Various fission fragments ranging from mass 84 to 144 with energies from 36 to 100 MeV as well as light ions such as alphas and tritons were used. Very good timing (10 ps RMS) and energy resolution (<2% RMS) with high detection efficiency (˜100%) was observed for single-crystalline detectors. Still, a significant pulse height defect as large as 50% charge carrier loss was observed. Polycrystalline diamond detectors presented still very good timing resolution (17˜34 ps RMS) but poor energy resolution and low detection efficiency (<30˜80%) due to incomplete charge collection. Based on these benchmark results, possible fission fragment detector designs and installation options at in-beam experiments will be discussed.

PS-8-23

Texas Active Target Detector Upgrade for 14O(α,p)17F Cross Section Measurement

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The 14O(α,p)17F is nominated to be an important reaction that strongly affects the light curves of the Type X-ray burst model [1]. In addition, the reaction rate is known to determine the break-out path from the hot CNO cycle to the rp-process at sufficiently high temperatures (T9 $>$ 0.5) [2]. While the reaction rate plays an important role, its large uncertainty due to lack of experimental measurement causes difficulties on the precise demonstration of astrophysical observables.

In order to constrain the reaction rate, the first direct measurement of the 14O(α,p)17F cross section will be performed at CRIB, RIKEN, with the Texas Active Target Time Projection Chamber (TexAT) which was developed at Texas A&M University [3]. The energy and position resolution of the detected charged particles from the reaction can be enhanced thanks to the three-dimensional tracking of the particles. Along with segmented silicon and CsI detectors around the field cage, the TexAT detector enables more precise cross section measurement as a function of center-of-mass energy. It has been used for many important nuclear research topics including proton/alpha elastic resonance scattering, direct fusion cross section, transfer reaction and neutron-induced reactions. The TexAT detector upgrade has been progressed to optimize the detector geometry for (α,p) cross section measurements at the Center for Exotic Nuclear Studies (CENS), Institute for Basic Science (IBS). The detector upgrade commissioning will be performed this summer to confirm its improvement of silicon detector position resolution and CsI detector energy resolution as well as compatibility of new parts. On the other hand, a high beam rate ($3*10^5$ pps) test of the TexAT detector using 14N+α elastic scattering was performed and its data is under analysis.

Detailed information of the TexAT upgrade and preliminary results of the commissioning experiments will be presented.

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Construction of the Multi-reflection time-of-flight mass spectrograph (MRTOF-MS) at RAON

PS-8-24

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The MRTOF-MS, which is allowed for the high precision (nuclear) mass measurement as one of the experimental devices of Rare isotope Accelerator complex for ON-line experiment (RAON), has been recently installed in the very-low energy experimental beamline of RAON. It will be utilized to measure the masses of the short-lived isotopes which are produced via proton-induced reactions at the ISOL ion source.

Based on the design of the MRTOF-MS at KISS (KEK Isotope Separation System) built in 2018, it was constructed in 2020, off-line commissioned on the next year, and will receive rare isotopes from the ISOL ion source at the end of 2022. It mainly consists of gas cell cooler-and-buncher (GCCB) to cool down the incident ions of less than 60 keV with helium buffer gas and manipulate the delivered ions - bunching and minimizing the emittance, and mass analyzer which receives ion bunches provided by the GCCB and makes multiple reflections of the ion bunch by using the electrostatic mirror potentials. Therefore, it allows for high mass resolving power due to the extension of the flight length or much longer TOF. During the off-line commissioning using thermal ion sources such as Cs and Rb, all subsystems have got optimized, from which all necessary parameters of the RF carpet system for the efficient ion extraction from the gas cell were obtained and those of the ion guide and the RFQ trap system as well. For the mass resolving power of our request, i.e., Rm ˜ 100,000, all related parameters, in particular the voltages of MRTOF mirror electrodes were carefully tuned, and as a preliminary result Rm ˜ 98,000 at 300 laps (equally TOF ˜ 6 ms) has been achieved.

We will perform online beam commissions using low-current beams provided by the ISOL ion source (133Cs and 23Na) to obtain the specification of the MRTOF-MS under actual experimental circumstances. In this contribution, the results of the off- and online optimization efforts of the MRTOF-MS system will be presented.

PS-8-25

RF Power Coupling for RAON RFQ

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A radio frequency quadrupole (RFQ) has been constructed as a front accelerator for a rare isotope accelerator facility. The RFQ has two power couplers that are operated simultaneously for high power operation to accelerate from proton to uranium. A coaxial transmission line was adopted to connect each power coupler and an 80kW solid state power amplifier(SSPA) which is consisted with combiners, circulators and 5kW unit amplifiers.

In this study, the coupling to the cavity with two power couplers was investigated for the failure of power units. Moreover, the operation scenario of the RFQ linac was also presented in considering the availability.

Design and Development of Control system for the RAON μSR facility in Korea using EPICS

PS-8-26

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A control system using EPICS was designed and developed to control and monitor components of the μSR facility at the Rare Isotope Science Project in Korea. In order to ensure that the components work normally during the facility operation, the status of components has to be checked continuously, moreover, the components have to be able to be controlled remotely. Experimental Physics and Industrial Control System (EPICS) is a real-time control system for scientific instruments such as particle accelerators, telescopes, and other large scientific experiments. All information in the facility is controlled by EPICS. Most commercial vacuum pumps have each communication protocol for serial communication. Other components, such as flow meters and thermocouples, send the desired value in forms of the current. An Arduino Uno module was added to transmit the current as a digital signal. The signals are sent to EPICS installed in Raspberry Pi 4 by serial communication. Components that are difficult to communicate with EPICS through serial communication are connected to EPICS via programmable logic controllers (PLC). Internal relay systems of PLCs are coded to control and monitor each component through the remote connector. Process variables in EPICS are controlled from a graphical user interface designed by Control System Studio and recorded in the Archiver appliance installed on the workstation.

PS-8-27

Proof of Principle of Newly Installed Second Arm at VAMOS++ Spectrometer

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The region below doubly magic 208Pb in the nuclear chart is important to understand nuclear interactions, nuclear shell evolution, and nuclear-astrophysical r-process. However, this region remains “a blank spot” in the nuclear chart due to the difficulties of producing them using conventional reactions such as fission or fragmentation.

We used multi-nucleon transfer reactions of 136Xe (7MeV/u) beam on 198Pt target to access this region. The experiment was carried out at GANIL. The VAMOS++ spectrometer [1] was used to detect and identify the projectile-like fragments (PLFs) at a grazing (40°) angle. Complementary target-like fragments (TLFs) velocity was measured by a newly constructed second arm, composed of a vacuum chamber and multi-wire proportional counter, which was installed at the 55º angle. The prompt and delayed gamma rays from nuclei of interest were measured by AGATA HPGe tracking array with 34 crystals [2] placed around the target position and 4 EXOGAM HPGe clover detectors [3] placed at the end of the second arm, respectively.

The second arm is essential for this experiment since the nuclides of interest are on the TLFs. The particle identification through the VAMOS++ spectrometer is only possible for the PLFs, thus, the TLFs are identified indirectly. By referring to the complementary PLFs identified by VAMOS, the information of TLFs measured by the second arm is used for indirect information to help to determine TLF identification. In this presentation, 1) the development process of the second arm, such as the GEANT4 simulation result, as well as the proof of principle result of the second arm from the experimental data, namely 2) detection of isomeric states from TLFs and 3) indirect TLF determination using coincidence VAMOS and the second arm will be discussed.

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PS-8-28

WISArD experiment: the precision frontier of BSM

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In the standard electroweak model, the weak current with a Vector – Axial-vector (V-A) form explains the weak interaction in a phenomenological context. However, the Lee-Yang Hamiltonian conserving Lorentz symmetry allows right-handed (V+A) as well as scalar, and tensor currents. For decades there have been efforts searching for such exotic currents as a test of the standard model. In particular, beta decay has been a powerful tool since the exotic currents are related to its kinematics [1]. Furthermore, its precision is comparable with high energy physics experiments [2].

The WISArD experiment, succeeding the WITCH experiment, has carried out the weak interaction studies at the ISOLDE facility. We employ the beta-delayed proton emission of 32Ar to search for a scalar current in beta-neutrino correlations. The extent of the proton kinetic energy shift provides information indirectly on the kinematics of beta-decay recoil nuclei, which is different between scalar- and vector-type interactions.

In the WISArD setup, the 30-keV 32Ar+ ions are implanted in the catcher foil at the center. The positrons emitted upwards are guided by the field of a superconducting magnet and detected by a scintillator. Silicon detectors surrounding the catcher foil measure the kinematic shift of the beta-delayed protons. A proof-of-principle campaign was executed in 2018 [3] and reached the 3rd best value for the angular correlation coefficients of vector decays. After upgrading the apparatuses, the first part of a new experiment was done in October 2021. We present details of the experimental devices and recent technical development for the setup.

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Particle identification of VAMOS++ spectrometer data using several machine learning techniques

PS-8-29

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The studies of low-lying excited states of the neutron-rich nuclei near the shell closures are one of the foremost topics of nuclear physics. The information of unstable, neutron-rich nuclei near N=126 magicity below 208Pb is crucial for understanding not only the nuclear structure of heavy nuclei but also the astrophysical r-process. However, the study of the south of 208Pb in the nuclear chart has been limited due to the difficulty of producing those nuclei.

We approached this region of interest using multi-nucleon transfer (MNT) reactions between 136Xe beam (7MeV/u) and 198Pt target. The experiment was performed at GANIL G1 hall. The VAMOS++ magnetic spectrometer [1] was set to grazing angle (40) with respect to the beam axis and used to identify projectile-like fragments (PLFs). The complementary target-like fragments' (TLFs) velocity vector was measured by the newly installed second arm set to the complementary angle (55). AGATA HPGe tracking array [2] with nominal configuration [3] measures the prompt gamma rays from the excited states of the produced nuclei. Additionally, the delayed gamma rays from TLFs were measured by EXOGAM HPGe clover array [4] located at the end of the second arm.

Unambiguous particle identification (PID) of PLFs from VAMOS++ data is the prerequisite for figuring out the origin of detected gamma rays in TLFs. Conventionally, multi-parameter analysis was carried out for PID due to the complex setup and reconstruction method. This method needs a lot of effort especially when ion energy has a broad range near a few MeV/u. Therefore, we developed the new method using several machine learning techniques for PID. The supervised learning with the deep neural network (DNN) and boosted decision tree (BDT) was used to calculate the ion energy which is critical for mass and ion charge states calculation. The mass and ion charge state resolution show improved value compared to reported in the literature using the conventional analysis technique [5].

The atomic number (Z) identification was treated as multi-class classification problem with soft labels. We used semi-supervised learning to identify the nuclear charge state of a particle and to calculate its confidence. Compared to the conventional E-E method, additional physical measurements such as velocity and mass can be used to deduce the nuclear charge state more accurately.

Improvement of the MHB quality factor and engineering design

PS-8-30

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The linear accelerator RAON, a component of the Rare Isotope Science Project, was developed to accelerate heavy ions from elements ranging from helium to uranium. The injector line consists of an Electron Cyclotron Resonance Ion Source, a Low Energy Beam Transport line, a Medium Energy Beam Transport line, and a Radio Frequency Quadrupole (RFQ). To improve beam quality, a multi-harmonic buncher (MHB) was proposed for inclusion before the RFQ. The MHB is needed to efficiently utilize two beams with different mass-to-charge (A/q) ratios. The MHB resonator operates at three frequencies (40.625 MHz, 81.25 MHz, 121.875 MHz), the fundamental frequency is half the frequency of the RFQ. Electric field simulations of the MHB were conducted using the CST Micro Wave Studio. The electrodes were designed as cone-type electrodes so that the electric field can be concentrated between the electrodes through which the beam passes. The electric field was optimized to account for structural changes such as gap length between electrodes, resonator position and other design details. The model optimized in the simulation tool is drawn through the 3D Inventor program.

PS-8-31

Development and characterization of new position-sensitive silicon strip detectors at CENS

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Direct reaction experiments in inverse kinematics are one of the best experimental tools to study a wide range of nuclear properties, providing a great probe into the nuclear structure of exotic nuclei and enabling the measurement of reactions relevant to many astrophysical scenarios. In order to fully exploit the next generation of radioactive ion beam facilities currently under development, the CENS group has devoted a large amount of effort to develop nuclear detectors, such as ATOM-X Active Target TPC and STARK Silicon Telescope Array, specially designed for direct reaction experiments. An instrumental part of these detectors is the Micron X6 position-sensitive double sided silicon strip detector. This custom-made detector is segmented in 4 strips on its ohmic side and 8 resistive charge-splitting strips on its junction side providing excellent position measurement of charged particles with a much smaller number of signals than traditional DSSSD with similar position resolution.

Detailed specifications of these detectors, optimized initial characterization methods and preliminary reports of their performance in terms of energy and position resolution will be presented.

β-NMR measurements of neutron-rich ^{21}O isotope for nuclear structure and materials science studies

PS-8-32

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In this interdisciplinary project, we investigate the nuclear structure of ^{21}O by measuring the ground-state electromagnetic moments using the combined technique of fragmentation-induced spin polarization and β-nuclear magnetic resonance (β-NMR) method. However, the ^{21}O isotope is not only important in such nuclear physics studies but also holds large potential importance in materials science. The fundamental importance of oxide-based systems both in technology and basic science has been strongly recognized, so that oxygen NMR (nuclear magnetic resonance) and NQR (nuclear quadrupole resonance) spectroscopy emerge as vital tools for materials characterization. NMR/NQR offers an element-specific, atomic-scale probe of the local environment, providing a powerful tool to probe local structure, local electric/magnetic field, and dynamics in solids. In spite of the almost ubiquitous presence of oxygen in inorganic and organic compounds, oxygen NMR/NQR studies have been relatively scarce in comparison with other nuclei. This is primarily due to the low natural abundance of the NMR-active isotope ^{17}O (0.038%). Isotopic enrichment is therefore necessary, often at considerable cost and efforts. Hence, the situation requires that artificial oxygen isotopes should be used by means of β-NMR/NQR, in which the nuclear spin precession signal is detected through the beta decay of a radioactive nucleus. This study will open new perspectives for condensed matter physicists and solid-state chemists to study oxide materials. The physics background, experimental methods and present status of the project will be covered in the presentation.

PS-8-33

Recent Upgrades and Mass Measurements with the TITAN MR-TOF Mass Spectrometer and Applications to Beam Composition

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TRIUMF's Ion Trap for Atomic and Nuclear science (TITAN) performs mass spectrometry and in-trap spectrometry on rare isotopes generated at the Isotope Separator and Accelerator (ISAC) facility of TRIUMF. Recently, the TITAN Multi-Reflection Time Of Flight (MR-TOF) mass spectrometer has made high-precision mass measurements of isotopes of interest for constraining astrophysical r-process and nuclear structure theory. It has also been applied to studying beam composition to characterize new targets and support implantation experiment.

The excellent mass accuracy, sensitivity and dynamic range of the TITAN MR-TOF makes it a powerful tool for performing these high-precision measurements. Since the MR-TOF's commissioning in 2017, it has undergone continuous upgrades, improving mass accuracy and precision, resolving power, efficiency, and species identification. A description of operation of the MR-TOF and improvements enabling TITAN's scientific program along with a selection of recent measurements will be presented, and their consequences discussed.

Beyond the N=50 shell closure: Magnetic moments, charge radii and masses of very proton-rich silver isotopes

PS-8-34

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The radioactive neutron-deficient silver isotopes around the *N*=*Z* region have been under scrutiny for several years, culminating with the debate around the two-proton decay in the (21+) isomer of ^{94}Ag. In addition to this unique isomer, the nuclear structure properties of ^{95,96}Ag are of considerable interest. Besides being on the path of the astrophysical rapid-proton (rp) capture process, these isotopes are expected to exhibit a multitude of phenomena due to their proximity to the *N*=*Z* line, including enhanced proton-neutron correlations, and shell-correction effects due to the nearby *N*=*Z*= 50 shell closure.

To access this region, an inductively heated hot cavity catcher laser ion source was tailor-made to enable high-efficiency stopping and extraction of silver produced via heavy-ion fusion-evaporation reactions. To interrogate nuclei with very low fusion-evaporation cross sections, the use of JYFLTRAP Penning trap with the PI-ICR method, enabled virtually background-free ion counting. This combination enabled resonance ionization spectroscopy of ^{96}Ag produced in the reaction ^{14}N(^{92}Mo, 2p8n)^{96}Ag with a peak detection rate of about one per 5 minutes. It is worth noting that, apart from the measurements presented here on, no optical spectroscopy has been performed on isotopes with both *Z* ¿42 and *N* ¡50, despite the many recent laser spectroscopy measurements performed on neutron-deficient isotopes of tin, indium and cadmium in just the last couple of years [1,2].

An evident feature stands out from the analysis of the data obtained on ^{96}Ag: A kink in the radii can be clearly observed as one crosses the *N*= 50 shell closure, a result which alone provides a compelling case for testing e.g. the very successful Fayans Density Functional Theory (DFT) calculations [3]. We present this, and the accompanying theoretical comparison [4], as well preliminary data for ^{95,96}Ag moments, radii, and masses. Furthermore, we discuss the outlook regarding ^{94}Ag and the continuation of the campaign with optical studies of proton-rich Pd, Cd, In and Sn isotopes.

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Off-line Tests and Performance of the Multi-Reflection Time-of-Flight Mass Spectrometer at SHANS

PS-8-35

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To precisely measure the atom masses and select isotopes of interest, a multi-reflection time-of-flight mass spectrometer has been built and successfully commissioned at the Spectrometer for Heavy Atom and Nuclear Structure (SHANS) which is located at Heavy Ions Research Facility in Lanzhou (HIRFL). Using a pulsed $^{133}Cs^{1+}$ ion beam generated through a Bradbury-Nielsen Gate (BNG) with an opening time of 150 ns, time-of-flight (TOF) has been measured at various conditions, TOF spread and symmetry of TOF spectrum have been optimized by two-dimensional potential scan at all electrodes. The mass resolving power reached 73 000 at a time-of-flight of 12 ms. The influence of power supply stability has been investigated in detail. In this talk, the setup, off-line test method, and main results will be presented.

PS-8-36

Design study of re-bunching systems for the RAON low-energy experiments

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RAON (Rare Isotope Accelerator complex for ON-line experiments) being constructed in Korea will provide both rare isotope and stable ion beams for nuclear physics as well as other applications, at a wide energy range of about 5 – 200 MeV/nucleon. One of low-energy experimental facilities, so-called KoBRA (Korea Broad acceptance Recoil spectrometer and Apparatus), will be utilized to produce rare isotope beams with a stable ion beam at an energy range of about 5 - 20 MeV/nucleon in early-phase experiments. The rare isotopes produced at a production target of KoBRA are identified to determine the nuclear charge and mass particle-by-particle from the measurements of position, energy loss, and time of flight together with a pulsed stable ion beam of less than 2.5 MHz. In addition, another facility, named as NDPS (Nuclear Data Production System), also requires a pulsed ion beam of less than 0.2 MHz repetition rate for time-of-flight measurements.

The bunch length of the ion beam increases during passing through a transport beam line from the end of the linac to a target, thereby requiring the re-bunching system for longitudinal focusing. The parameters of the re-bunching systems for KoBRA and NDPS were evaluated by electromagnetic field calculations and particle tracking simulations.

An IH-DTL (Interdigital H-mode Drift Tube Linac), designed as a re-buncher for KoBRA, is being manufactured since June 2022. The existing HWR (Half-Wave Resonator) cavities are considered as a re-buncher for NDPS. We will present the status of the re-bunching systems for the RAON low-energy experimental facilities.

Degradation of Lithium fluoride thin targets on Carbon Backing Irradiated with 68 MeV O-17 Beams at EMMA Facility of TRIUMF

PS-8-37

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To analyze the cause of destruction of lithium fluoride thin targets on carbon backing through a measurement of the fusion of He-4 and O-17, we theoretically estimate the lifetimes of carbon and LiF films through sputtering, thermal evaporation, and lattice damage. Then, we compare them with the lifetime obtained from the experiment. Sputtering yields and thermal evaporation rates in carbon and LiF films remain too low to be considered in the calculation. We estimate the lifetime of the target by lattice damage of carbon and LiF film using previously reported model. In the experiment, elastically scattered particles of target and beam over the time are detected by surface silicon barrier (SSB) detector so that the beam flux and target content degradation can be monitored during an experiment. The areas in the targets exposed to different intensities and fluences are degraded then perforated in around the beam diameter spot size. The calculated lifetime determined by lattice damage agrees well with the time consumed until the disposal of the target in the experiment. Overall, the target thickness tends to decrease linearly over the beam fluence. However, the thickness also exhibits an increasing interval after fluence is approximately 1.2×10ˆ16 ions/cm2, benefitting the target lifetime. The lifetime of thin LiF film as determined by lattice damage is calculated for the first time using a lattice damage model, and the calculated lifetime agrees well with the experimentally observed one. In the experiments using a thin LiF target to induce nuclear reaction, this study suggests methods to predict the lifetime of the LiF film and arrange the experimental plan for increased efficiency.

PS-8-38

Properties of the near-threshold proton-emitting resonance in ^{11}B

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The study of atomic nuclei close to the drip lines and beyond is one of the major current directions of nuclear science. At limits of nuclear stability, rare decay processes were discovered, especially for nuclei with the halo structure. A very particular case is the β-delayed proton emission of the one-neutron halo nucleus [1] that was directly observed in ^{11}Be with high intensity [2]. It was explained by the existence of the near-threshold proton-emitting resonance in ^{11}B [3] which was recently confirmed by the experiment with E_r = 182 keV, Γ_p = 4.4 keV, and $J^\pi = 1/2^+$ [4]. In this talk, we present the theory interpretation for this resonance [5]. Furthermore, the decay mode is expected for rare isotopes ^{19}C and ^{31}Ne [1] that can be produced by KOBRA.

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Integration system, called BYACO, of analysis, devices, detectors, and DAQ to enable full capabilities of online experimental execution

PS-8-39

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At RIKEN RIBF, RI beams are produced by the projectile-fragment separator BigRIPS [1]. RI-beam separation and PID become difficult when the atomic number of the RI beam is large or the RI-beam energy is low, since the electrons of the ion are not fully stripped. In addition, for the slowed-down RI beams, the prediction accuracy of the energy loss in a thick material is insufficient. Obtained data as a development of such RI beams were compared [2,3] with predictions by LISE^{++} [4]. Comprehensive analysis methods and specialized simulation tools are often developed [2,3]. For a quick RI-beam delivery after the completion of RI-beam developments, it is important to handle the comprehensive analysis methods and simulation tools online. If the analysis, beamline devices, detectors, DAQ, are integrated, more advanced operations could be executed during experiments online.

In this conference, we will introduce the developed integration system called BYACO (BeYond Analysis, Control, or Operation alone). Implemented examples of applications and perspectives will be presented.

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PS-8-40

Effect of large Q fluctuation in gas to Z identification for heavy RI beams at RIKEN-RIBF energy

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RI beams with a wide range of the atomic number Z are produced utilizing a 345-MeV/u U-238 beam at RIKEN RIBF. For the Z identification of the RI beams, ΔE in the P10 gas (Ar 90%:CH4 10%) is measured [1]. It has been observed that the Z resolution becomes gradually worse, as Z of RI beams increases [2]. The reason is that the energy-loss straggling is drastically enhanced when the number of the charge-state changes in the gas, $N_{\Delta Q}$, is non-zero value and low [3]. As $N_{\Delta Q}$ increases, the measured ΔE is related not to Z but to the average of the charge state $< Q >$. In the previous experience of RI beams with Z˜86 [4], the Z identification was succeeded, and there was no drastic distortion in the Z distribution, even though σ_z is worse to be 0.4. This fact suggests that ¡Q¿ was observed as numbers including decimals in a moderate resolution even though $N_{\Delta Q}$ is low. This is not simply understood only from the mean free path as shown in Ref. [3]. Therefore, we investigated an underlying mechanism using GLOBAL [5] and ATIMA [6] for the charge-changing cross sections and energy losses, respectively. In this conference, we will show the results and discuss a benefit of the Kr and Xe-based gases for the Z identification. The experimental study about the Xe-based gas and comparison with the P10 gas will be presented by M. Yoshimoto et al [7].

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Charge state fluctuations of heavy ion beams inside ionization chambers

PS-8-41

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With the development of unstable nuclei beam generation and separation capabilities, the field of unstable nuclei research has expanded to include the measurement of various nuclei. At RIKEN, new isotopes have been discovered one after another, and the research has been expanded to the neutron-rich side or the region with large atomic number Z, such as 180Er with the largest Z, $Z = 68$. Currently, there are high expectations for the search for new isotopes in the upper right corner of the nucleus chart. However, previous studies have shown that the Z resolution for identifying nuclear Z deteriorates in regions with large Z, which poses a major challenge.

Ionization chambers with good energy resolution for low mass are often used to measure the energy loss ΔE for particle identification in heavy ion beams. However, it has been found that the energy resolution of ion chambers deteriorates as Z increases. This phenomenon was explained by a Monte Carlo simulation of the charge state fluctuation caused by charged particles passing through the ionization chamber inside the detector and reproducing the experimental values. The experiments were performed at the National Institute of Radiological Sciences (NIRS) using a secondary beam of $Z = 22$ ˜ 55 generated by injecting a primary beam of 136Xe into a production target, Be. In this presentation, we will give an overview of the measurements and the results.

PS-8-42

Hyperpure ISOL beams of Cd isotopes at ISOLDE

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Cadmium isotopes were among the first beams produced at the CERN-ISOLDE facility over fifty years ago [1]. Due to its higher volatility compared to neighboring elements cadmium lends itself well for a purification by an isothermal chromatography line placed between target and ion source. Later the element selective RILIS technique provided additional chemical selectivity [2]. A combination of both methods has already been successfully used for Zn beams [3] and certain experiments with Cd beams.

Recently a variant of this “quartz transfer line” has been designed that enables further improved isobaric suppression via an improved temperature control of the transfer line. We present the first results of “hyperpure Cd beams” obtained with such a target and ion source unit.

Yields and beam purity are reported for resonantly laser ionized $^{117-131}$Cd isotopes produced in a UC_x target with “neutron converter”. Measurements have been performed by on-line gamma-ray spectroscopy at the ISOLDE Decay Station (IDS) and by off-line gamma-ray spectroscopy respectively. Moreover, relative intensities were derived from data of the COLLAPS collinear laser spectroscopy experiment. The observed isomeric ratios of odd-mass Cd isotopes are compared to those obtained by spallation in a molten tin target.

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Muonic X-ray Spectroscopy on Implanted Targets

PS-9-1

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Muonic X-ray Spectroscopy is a technique that utilizes the properties of the muon to gain information about the structure of the atom and the nucleus. When interacting with an atom, the muon can be captured in a high principal atomic quantum number state. Once this occurs, it rapidly decays through the muonic energy levels to the atomic ground state, emitting high-energy X-rays (up to 10 MeV). This decay radiation can subsequently be used to identify the muonic energy levels, which reveal information about nuclear properties, such as the nuclear electric quadrupole moment through the hyperfine interaction [1] or the nuclear charge radius from finite size corrections [2].

Since 2017, the muX collaboration at the Paul Scherrer Institute in Switzerland has used a high-pressure hydrogen cell with a small deuterium admixture to improve the muon capture efficiency, allowing for the measurement of target quantities as small as 5 µg [2]. Furthermore, a measurement performed in 2018 showed that about 27% of the muons are transmitted through a 100 nm layer of graphite. This result indicates the possibility of muonic X-ray spectroscopy on implanted targets. Such targets would provide a protective layer to chemically reactive samples that could be manipulated, or allow to apply mass separation combined with implantation to produce isotopically pure samples.

In the 2022 muX campaign at the πE1 beamline at PSI, glassy carbon (SIGRADUR K) samples, each implanted with Au-197 at different energies, will be measured. Thus, the depth dependence of the muon capture efficiency can be investigated. To guarantee swift measurements while optimizing the method, samples are being prepared with a mass about an order of magnitude larger than the minimal requirements. However, this corresponds to particle fluences in the order of $10^{17} cm^{-2}$, which is reaching the self-sputter limit. TRIDYN simulations [3, 4] suggest an unusual behavior of self-sputtering during implantation showing a fast drop in implanted fluence after a maximum is reached, instead of a saturation behavior at maximum capacity. Rutherford backscattering measurements of the different targets is thus performed to validate the TRIDYN simulations.

In this contribution, we shall report on the Au implantation in glassy carbon, from simulation and experimental point of view, as well as present preliminary results from the 2022 muX campaign and the implications for future muonic X-ray measurements with implanted radioactive samples.

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Development and optimization of the digital electronic for the search of new super heavy element at RIKEN on GARIS-III

PS-9-2

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With the extension of the nuclear chart to more extreme regions, the precise and accurate measurement of the decay properties also become more and more challenging. Part of the solution to tackle down some of these challenges is to improve the detection setup of the nuclear experimental setup. One of these solutions is the transition to a fully digital electronic acquisition system.

The Super Heavy Element (SHE) program at RIKEN is currently undergoing such transition to digital electronics for the GARIS II/III detection system [1]. The GARIS II/III implementation of digital electronics uses Pixie-16 revF modules designed and manufactured by XIA LLC (16 bits resolution, 250 MHz sampling [2]). This transition opened the door to a triggerless overall system, the drastic reduction of the dead time in comparison to the analog electronic currently in-use. Moreover, the direct access to the waveform of detected events also triggered the development and investigation of the pulse shape analysis and its performance in the SHE mass region. These electronics modules allow for the online detection of pile up event channel by channel. Combined with the recent upgrade to fast charge sensitive preamplifiers (CREMAT Inc. CR-110 and CR-111 [2]), it led to a reduction of the dead time of the overall system down to 64 ns after implantation. This is a drastic reduction compared to the counterpart analog electronic currently in-used, which only allow 2 events detection within a 70 μs windows (with a 5 μs dead time after the first event).

In addition, the optimization of the energy parameters is crucial to insure the best performance of such system. The onboard energy measurement is performed using some implementation of the Jordanov algorithm [4] which transform the standard exponentially decaying signal of a preamplifier into a trapezoidal shape. This shape is defined by two main parameters (integration time and flat top duration). The optimization of the parameters led to a reduction of the Full Width at Half Maximum (FWHM) of the alpha spectrum of 5 keV, compared to the analog electronic (from 31 to 26 keV), at 7.133 MeV using the production of the 207Ra. Moreover, with the direct access to the waveform of individually recorded events, we developed the Pulse Shape Analysis (PSA) of these data. Indeed, thanks to the very fast response-time of the CR-111 preamplifier the rising edge of waveform are in the vicinity/faster than the typical collection time in the Silicon detector given the optimized condition of operation (-5 C, 80 V). The main component of background in the alpha spectrum comes from the passing through particle (H-like and He-like) in the implantation detector. Most of them can be removed using the veto detector placed directly behind the implantation detector. However, based on this PSA analysis, we determined that we could reduce this background by additional 50 to 60% compared to the veto-detector suppression only.

The detail of the optimization of the digital electronic and the analysis of the data produce will be presented.

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Magnetic resonance imaging (MRI) by β-ray tracking using scintillation-fiber detectors

PS-9-3

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We are currently studying the nuclear physics and material science using β-NMR technique, that is to observe the nuclear magnetic resonance (NMR) by using the asymmetry of the β-ray angular distribution emitted from spin-polarized nuclei. In this research, we are developing a β-MRI technique that applies the β-NMR method to magnetic resonance imaging (MRI), which is already widely used in the medical and other fields. This new technique is expected to enable MRI using many nuclides, including carbon and oxygen, which have been unavailable by conventional MRI using nuclei. The β-MRI device to be developed will be capable of identifying the source of β-ray emission in three dimensions by tracking β-rays in two dimensions with a position detector manufactured using scintillation fibers and narrowing the z-axis size of the beam to irradiate the sample. In January 2022, we developed a position detector that counts β-rays using a MPPC (multi-pixel photon counter) with scintillation fibers aligned parallel to the beam axis and its orthogonal axis and tested its performance using a spin-polarized 12B beam at HIMAC in National Institutes for Quantum Science and Technology. As a result of the performance test, the position detectors were able to identify the trajectory of β-rays in two dimensions.

PS-9-4

DFT calculations of Ti-based molecules clustering with Ar for laser-based enrichment of stable isotopes

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The selective production of radioisotopes with low-energy particle accelerators based on fusion-evaporation reactions, or in nuclear reactors with neutron capture, partially relies on the availability of isotopically pure target material. For example, the production of the medical radioisotope Lutetium-177, a rising star in nuclear medicine, depends upon the availability of Ytterbium-176 as target material (natural abundance 13%). Similarly, isotopes of Calcium (Z=20) and Titanium (Z=22) are promising for the production of the medically relevant isotopes Scandium-43, Scandium-44 and Scandium-47. However, both elements have a fragmented natural distribution across 6, respectively 5, stable isotopes. Moreover, Calcium-48 (natural abundance 0.185%) is the most neutron-rich stable isotope that can be used as a beam to synthesize superheavy elements.

Within PRISMAP, the European programme for medical radionuclides, we are investigating the possible enrichment of Titanium and Calcium stable isotopes by means of Separation of Isotopes by Laser Assisted Retardation of Condensation (SILARC). Titanium or Calcium-containing molecules are injected in a gas cell containing Argon as a buffer gas and released via a nozzle creating a supersonic jet. The temperature drops to ~15K, at which point Argon atoms cluster around the molecules. If an isotopomer can be selectively excited by an infrared laser, the clusterization can be prevented and the molecule experiences a drag force through the jet, physically separating it from the clusters. As a first step in this development, Density Functional Theory (DFT) calculations have been performed on Titanium-containing molecules, to determine the ground-state configuration of the molecules (geometry and spin state), their interaction with Ar, and to calculate the frequencies of their vibrational modes. Isotope-selective transitions were identified, mostly in the mid-infrared region. In this contribution, the results from those calculations for simple molecules (TiFx (x=1-4), TiHx (x=1-4)) and complex molecules (Ti[OEt]4, Ti[OPr]4) will be presented. The infrastructure to investigate SILARC of Titanium at CERN and KU Leuven will be introduced.

Sustainability of enriched isotope supply for medical radionuclide production

PS-9-5

Ulli Köster

Production of medical radionuclides often requires the use of isotopically enriched targets. Depending on the natural abundance of the isotope in question and the chemical properties of the element to be enriched, the throughput of isotope enrichment facilities varies considerably. Different production paths may lead to the same radionuclide, e.g. (p,n), (p,2n), (p,α) or deuteron or α induced reactions. These paths will differ considerably in production yield, in the type, energy and maximum intensity of the primary beam, but also in the employed enriched isotope target. The overall production effort, i.e. the production costs, of the radionuclide production will depend on all these parameters. Considering these interdependencies the putatively obvious choice of the reaction with the highest yield does not necessarily provide the most economic or most sustainable production path.

Based on selected case studies I will present ways to choose the most sustainable production path that makes best use of available enrichment and accelerator capacities. In particular, cases of emerging radionuclides for medical applications will be discussed that are made available within PRISMAP – The European medical radionuclide programme.

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PS-9-6

A "makeshift spallation neutron source" for neutron-rich Te isotopes at ISOLDE

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High-energy (GeV)-proton-induced fission generates a wide isobaric distribution ranging from neutron-rich to neutron-deficient isobars. This can lead to disturbing background of neutron-deficient, easily surface ionized isotopes, such as Rb or Cs, in particular when weakly produced neutron-rich isotopes around N=50 or N=82 are aimed for. Such background can be significantly reduced by the use of a so-called "neutron converter" [1], typically a tungsten rod mounted parallel to the target that serves as miniature spallation neutron source. Mainly the laterally emitted part of the evaporation neutron spectrum will induce MeV-neutron-induced fission that provides an isobaric distribution centered on the neutron-rich side.

Only upon request the ISOLDE target and ion source units are constructed with an integrated tungsten neutron converter. Thus, the use of a neutron converter has to be planned well ahead in the schedule and cannot be decided ad hoc during an experiment. However, in principle, the massive copper current leads that are present in every target unit could also serve as "makeshift neutron converters". The secondary neutron yield of such medium mass spallation targets is reduced with respect to tungsten, but, at least for certain applications it can provide sufficiently intense and pure beams of neutron-rich isotopes.

We present the first test of such a makeshift neutron converter at the example of beams of tellurium isotopes. Yields, isomeric ratios, isobaric contaminants and release properties were measured for resonantly laser ionized $^{112-137}$Te isotopes and isomers, produced in a UC_x target, either irradiated directly with 1.4 GeV protons or with secondary neutrons that were either produced in a makeshift Cu neutron converter or in a standard W neutron converter respectively. Yields were determined by γ-ray spectrometry and ion current measurements or derived from the relative intensities observed in the COLLAPS collinear laser spectroscopy experiment respectively.

References

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The CERN-Nano Laboratory – A research and development facility dedicated to the production of nano materials PS-9-7

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The CERN-Nano Laboratory is a recent extension to the Class A Laboratories, CERN's only laboratory with the capabilities to manipulate and change the chemistry of highly radioactive open-sourced materials.

Both the CERN-ISOLDE (Isotope Separator On Line DEvice at CERN) and CERN-MEDICIS facilities (MEDical Isotopes Collected from ISolde) have the resources to create radioactive ion beams using irradiated targets from the proton beam of the Synchro Cyclotron facility at CERN. These targets are operated at very high temperatures of 2000∘C and above, to accelerate diffusion through the grains of the target material. The elevated temperature leads to sintering of the material over time, resulting in larger grains and increased diffusion times. A lever to shorten the diffusion time is the decrease of the particle size. Nano-structured materials have shown to exhibit unmatched release properties, promising higher overall yields of short-lived isotopes despite their lower density and associated production rate. The new CERN-Nano Laboratory has the abilities to reduce the grain size of these target materials resulting in highly porous nano structure which encourages a higher release rate for short lived isotopes and generally higher isotopic yields.

With the project in full swing, the aim is to start producing nano materials by the end of 2022.

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