Advances in Radioactive Isotope Science

Sunday 28 May 2017 - Friday 02 June 2017

Book of abstracts
Logistics and Welcome
Brad Sherrill (NSCL), Jens Dilling (TRIUMF) and the local organizers

Plenary Monday

QED and the Hyperfine-structure Puzzle in Hydrogen-like and Lithium-like Bismuth

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The possibility of testing quantum electrodynamics (QED) in very strong fields by laser spectroscopy on heavy highly charged ions has been opened by the first observation of the hyperfine splitting in hydrogen-like bismuth in 1994 [Klaft et al. Phys. Rev. Lett 73, 2428 (1994)]. The electrons in these systems experience the strongest magnetic fields available in the laboratory, but the significance as a test for QED of this and following experiments on other species was limited by the unknown magnetic moment distribution inside the nucleus. However, it was suggested that a so-called specific difference between the hyperfine splittings in hydrogen-like and lithium-like ions of the same isotope can be used to cancel nuclear structure effects and provide an accurate test of QED [Shabaev et al., Phys. Rev. Lett. 86, 3959 (2001)]. The transition in Li-like Bismuth was observed for the first time in 2011 at the Experimental Storage Ring ESR located at the GSI Helmholtzzentrum für Schwerionenforschung in Darmstadt [M. Lochmann et al., Phys. Rev. A 90, 030501 (2014)]. Yet the accuracy of the result was limited by the calibration of the electron cooler voltage, determining the ion velocity. Here, we report on improved laser spectroscopic measurements on bismuth ions of both charge states (209Bi82+ and 209Bi80+) at the ESR. The accuracy was improved by about an order of magnitude compared to the first observation in 2011. We will present the measured transition energies of both hydrogen- and lithium-like bismuth and the experimentally determined value for the specific difference in 209Bi which is in contradiction with theoretical predictions. Possible reasons will be discussed and ways to further investigate this puzzle by laser spectroscopy on radioactive species will be discussed.

Plenary Monday

Ion Traps for Precision Experiments at TRIUMF

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Ion traps are of growing popularity at rare-isotope-beam facilities due to their textbook-like conditions and tailorability. This versatility is exemplified at TRIUMF’s Ion Trap for Atomic and Nuclear science (TITAN) facility, where ion traps are used for beam preparation and high-precision measurements. Penning trap mass spectrometry has provided insight into the evolution of the N = 20 shell in the island of inversion, nucleosynthesis via the r-process, and the unitarity of the quark-mixing matrix. In-trap decay spectroscopy research has focused on branching ratios to investigate the double-beta-decay problem and now includes studies of the role of electronic structure in nuclear decay. Moreover, investigations with preparatory traps are being used to extend the reach of TITAN, by reducing beam contamination, improving beam availability beyond ISOL-produced beams, and increasing ion bunch size. A selection of recent highlights and advances will be presented.
Plenary Monday

The Search for Fundamental Symmetry Violation in Radium Nuclei

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Electric dipole moments (EDMs) are signatures of time-reversal, parity, and charge-parity (CP) violation, which makes them a sensitive probe of expected new physics beyond the Standard Model, such as supersymmetry. No experiment has yet observed a non-zero EDM to challenge the Standard Model. Due to its large nuclear octupole deformation and high atomic mass, the radioactive Ra-225 isotope is a favorable EDM case; it is particularly sensitive to CP-violating interactions in the nuclear medium. We have developed a cold-atom approach of measuring the atomic EDM of Ra-225 atoms held stationary in an optical dipole trap. We previously demonstrated this technique with an initial experimental upper limit of |d(225Ra)| < 5 \times 10^{-22} \text{ e-cm (95\% C.L.)}, and have since improved this limit 36-fold to 1.4 \times 10^{-23} \text{ e-cm}. This is not only the first time laser-cooled atoms have been used to measure an EDM, but also the first time the EDM of any octupole deformed species has been measured. Upcoming improvements are expected to dramatically improve our sensitivity, and significantly improve on the search for new physics in several sectors. This work is supported by U.S. DOE, Office of Science, Office of Nuclear Physics, under contract DE-AC02-06CH11357.

Magnetic Moment Measurement of Isomeric State of Cu-75 Using Spin-aligned RI Beam at RIBF

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Unstable nuclei with extremely unbalanced proton-to-neutron ratio often exhibit evolved shell structure and collectivity such as vibrated/deformed shapes, which compete with each other to determine the resultant structure. The nuclear magnetic moment is one of the important observables with which we can catch a glimpse into the competition.

A technique to orient the nuclear spin is necessary for the magnetic moment measurement. Recently a scheme of the two-step reaction was developed to produce high spin alignment (rank-two orientation) in RI beams [1]. This scheme realizes high spin alignment as well as high production yield of RI beams by combining a technique of momentum dispersion matching at the beam transportation. It has opened up opportunities to produce spin alignment for unstable nuclei, for which the spin alignment would have tended to significantly attenuate if the conventional scheme was employed because of the mass difference between a projectile and the final fragment.

The two-step scheme was employed in the magnetic moment measurement of the isomeric state of the neutron-rich nucleus Cu-75. The experiment was carried out at RIBF. The Cu-75 beam with spin alignment reaching 30% was produced from a primary beam of U-238 via an intermediate product of Zn-76. For the measurement of the magnetic moment, a method of time-differential perturbed angular distribution (TDPAD) was employed. Owing to the high spin alignment realized with the two-step scheme, the oscillation in the TDPAD spectrum was observed with significance larger than 5 sigma. The magnetic moment of the 66.2-keV isomer, which is one of the two low-lying isomers in Cu-75, was determined for the first time.

In this talk, the magnetic moment measurement employing the two-step scheme will be introduced and the result of the experiment of Cu-75 will be presented. Discussions on the competition between shape and shell at the neutron-rich Cu isotopes, through the precise analysis of the magnetic moment with a help of the state-of-the-art Monte Carlo shell model calculation, will also be given.

References:
Plenary Monday

Explosive Nucleosynthesis of Heavy Elements: An Astrophysical and Nuclear Physics Challenge

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Half of the elements heavier than iron are produced by the r process under extreme conditions. To identify its site remains one of the major challenges in nuclear astrophysics. Advances in the description of neutrino-matter interactions and its implementation in core-collapse supernova modelling have led to the conclusion that supernova explosions only contribute to the production of elements with Z < 50. Compact binary mergers are currently considered the best candidate for the main r-process site. These events are expected to produce gravitational waves, likely to be observed by the LIGO collaboration, and eject large amounts of neutron-rich material where the r process operates. In this talk, I will discuss the important role of nuclear physics to determine the r-process yields from compact binary mergers. In addition to neutron captures and beta decay, fission rates and yields of superheavy neutron-rich nuclei are fundamental to understand the r-process dynamics and nucleosynthesis. Mergers constitute also ideal candidates to directly observe the r-process via an electromagnetic transient due to the radioactive decay of r-process material. This type of event, known as kilonova, may have already been observed associated with the gamma-ray burst GRB 130603B.

Plenary Monday

Advances in Explosive Nuclear Astrophysics

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Breathtaking results from the Planck satellite mission and Hubble space telescope have highlighted the key role modern Astronomy is playing for our understanding of Big Bang Cosmology. However, not so widely publicized is the similar wealth of observational data now available on explosive stellar phenomena, such as X-ray bursts, novae and Supernovae. These astronomical events are responsible for the synthesis of almost all the chemical elements we find on Earth and observe in our Galaxy, as well as energy generation throughout the cosmos. Regrettably, understanding the latest collection of observational data is severely hindered by the current, large uncertainties in the underlying nuclear physics processes that drive such stellar scenarios. In order to resolve this issue, it is becoming increasingly clear that there is a need to explore the unknown properties and reactions of nuclei away from the line of stability. Consequently, state-of-the-art radioactive beam facilities have become terrestrial laboratories for the reproduction of astrophysical reactions that occur in explosive stellar events. In this talk, both direct and indirect methods for studying key astrophysical reactions using radioactive beams will be discussed.

Plenary Monday

Direct Measurements of α-capture Cross Sections Relevant for Nuclear Astrophysics

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Since helium is the second most abundant element in the universe, there are numerous reaction rates involving α-particles that play a key role in nuclear astrophysics. For instance, some (α,p) reactions have been found to be fundamental for the understanding of X-ray bursts and the production of 44Ti in core-collapse supernovae. Furthermore, some (α,n) reactions are considered to be important neutron sources in different astrophysical scenarios. Direct measurements of these reactions at relevant astrophysical energies are experimentally challenging because of their small cross sections and the intensity limitation of radioactive beams. In this talk I will describe a novel technique to study (α,p) and (α,n) reactions using a Multi-Sampling Ionization Chamber (MUSIC), a simple and highly efficient active target system with a segmented anode that allows the investigation of a large energy range of the excitation function. Recent results on the direct measurement of (α,n) and (α,p) reactions in the MUSIC detector will be presented. This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under contract number DE-AC02-06CH11357. This research used resources of ANL’s ATLAS facility, which is a DOE Office of Science User Facility.
Plenary Monday

Neutron Capture Reactions for the Astrophysical r process

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The astrophysical r process is responsible for the synthesis of about half of the isotopes of the heavy elements. Although the general characteristics of the process have been known for a while, the astrophysical site where it takes place has not been unambiguously determined. Efforts to better understand this important process span across many fields, including astronomical observations of metal-poor stars, modeling of the possible scenarios, sensitivity studies, nuclear theory calculations and nuclear experiments. One of the nuclear inputs that have a large impact on the final abundance calculations is neutron-capture reaction rates. These reactions are practically unconstrained far from stability due to the difficulty in studying them with direct techniques. As a result, astrophysical calculations have to rely on theoretical models, which differ from each other by factors of 10-1000. Therefore, indirect experimental approaches are required, and this talk will present the development of a new technique to experimentally constrain these important (n,γ) reaction rates far from stability. The relevant experiments were done at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University using the γ-calorimeter SuN. New results in the mass region of A=70 and the impact on r-process calculations will be presented.

Plenary Monday

Unveiling New Features in the Exotic Landscape of Light Nuclei with Direct Reactions

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Radioactive (RI) beams are allowing us to uncover the unknown properties of nuclei at the extremes of nuclear binding. This is leading to revelation of new phenomena associated with exotic structures like nuclear halo and skin that stretch beyond the bounds of our conventional knowledge. The evolution of neutron skin/surface in neutron-rich nuclei can cause mutation of the nuclear shell structure and give rise to exotic excitation modes such as soft dipole resonance states. The new features in exotic nuclei challenge our understanding of the nuclear force. Reaction spectroscopy with both ISOL and in-flight RI beams offer complementary avenues that have different sensitivities to different characteristics of the exotic nuclei. The presentation will discuss how direct reactions with the low-energy re-accelerated beams at TRIUMF and the IRIS reaction spectroscopy facility with solid H₂/D₂ targets have opened access for obtaining some precise spectroscopic information of exotic nuclei. Recent explorations of unbound states in light nuclei around the drip-lines will be presented. It will be shown that the low-energy scattering opens a new avenue to constrain the nuclear force with its ability of connecting to the ab initio theory. The relativistic energy in-flight beams allow us to probe into the nucleon distribution and nuclear radii that characterize the exotic nuclear halo and skin. Recent measurements at the GSI fragment separator FRS will be reported to elucidate the development of neutron skin and evolution of nuclear halo correlations in neutron-rich nuclei.
Plenary Monday

Four-body Continuum Effects in d+^{11}Be Elastic Scattering

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The main goal of the Continuum Discretized Coupled Channel (CDCC) method is to solve the Schrödinger equation for reactions where the projectile presents a cluster structure, and a low dissociation energy. The CDCC method has been introduced forty years ago [1] to describe deuteron induced reactions. Owing to the low binding energy of the deuteron, it was shown that including continuum channels significantly improves the description of d+nucleus elastic cross sections [1, 2]. The simplest variant of CDCC describes scattering of a two-body nucleus with a structureless target, but extensions to three-body projectiles have been performed recently (see, for example, ref. [3]). The projectile continuum is approximated by a finite number of square-integrable states, up to a given truncation energy.

We present here a new development of the CDCC method, which aims at describing reactions where the projectile and the target have a low separation energy. This leads to four-body (or more) calculations. Since continuum states are included in both colliding nuclei, the number of channels can be extremely large. We solve the coupled-channel system by using the R-matrix method on a Lagrange mesh [4].

A first application is presented for d+^{11}Be elastic scattering and breakup, which have been measured recently at E_{cm}=45.5 MeV [5]. The ^2H and ^{11}Be nuclei are defined by ^2H=p+n and ^{11}Be=^{10}Be+n structures. We choose the Minnesota potential [6] as nucleon-nucleon interaction, and the Koning-Delaroche global potential [7] as nucleon-^{10}Be optical potentials. We show that including continuum states of ^2H and of ^{11}Be is necessary to reproduce well the experimental data.

References:


Plenary Monday

Transfer Reactions with Isomeric Beams

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Nuclear reactions induced by isomeric beams have long been considered an extremely attractive tool for nuclear structure, nuclear reactions and nuclear astrophysics studies. One of the most interesting cases is in ^{26}Al, where a 0⁺ isomer is located 228 keV above the 5⁺ ground state. Proton captures on both, the ground state and the isomeric state, could have a direct impact on the abundance of ^{26}Al in the Galaxy.

In this talk, I will discuss our efforts to develop and characterize an isomeric ^{26}Al^{18} beam with sufficient intensity, purity, high isomer-to-ground state ratio and energy resolution to study transfer reactions induced by the 0⁺ isomer in ^{26}Al. Results on the measurement of the ^{26}Al^{18}(d,p)^{27}Al reaction and its astrophysical implications will also be presented.
Plenary Monday

Isospin Symmetry Studies Using Direct Reactions on Fragmentation Beams

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The neutron-proton exchange (isospin) symmetry results in striking symmetries in nuclear behavior between isobaric analogue states (IAS). The very small differences in excitation energy between the IAS can be interpreted in terms of Coulomb, and other isospin-non-conserving, effects. The analysis of these energy differences has been shown to be a sensitive probe of nuclear structure effects and provides stringent tests of model calculations (e.g.[1-5]). New experimental techniques have been applied in the last few years to access excited states in isobaric multiplets of larger isospin through spectroscopic studies of proton-rich nuclei heading towards the proton drip-line.

Knockout reactions have recently been shown to provide a successful and versatile technique for accessing states of interest in proton-rich nuclei for isospin-related studies. The direct nature of the 1-nucleon and 2-nucleon knockout mechanism yields selective population specific analogue states within a multiplet, allowing studies of isospin-symmetry breaking - see e.g. [6]. In this talk, the latest results using knockout reactions on radioactive beams at NSCL will be presented, including an analysis of mirrored knockout reactions and population of high-spin states through knockout from a high-spin isomer [7]. Theoretical analysis of both the reaction cross sections and isospin-symmetry breaking effects across the multiplets in the f_{7/2} shell will be presented.

In the shape-coexistence region around A~70, the strongly competing nuclear shapes have been predicted to yield the potential for the breakdown of isospin symmetry across a multiplet (e.g. [8]). To test these ideas, the study of the full A=70 isobaric triplet has been the subject of a number of experimental studies, to examine the extent to which isospin symmetry is retained. The recent identification of excited states in 70Kr [9] now completes this triplet. These data and their interpretation will be presented.

References:

Advances in Radioactive Isotope Science / Book of abstracts

Plenary Monday

**np Pairing Viewed From Transfer Reactions**

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Neutron-proton pairing is the only pairing that can occur in the T=0 and the T=1 isospin channels. T=1 particle-like pairing (n-n or p-p) has been extensively studied unlike T=0 neutron-proton pairing. The over-binding of N=Z nuclei could be one of its manifestation.

Neutron-proton pairing can be studied by spectroscopy as in ref. [1]. We have studied it through transfer reactions in order to get more insight into the relative intensities of the two aforementioned channels. Indeed, the cross-section of np pair transfer is expected to be enhanced if the number of pairs contributing to the populated channel is important.

Neutron-proton pairing is predicted to be more important in N=Z nuclei with high J orbitals so that the best nuclei would belong to the g\(_{9/2}\) shell [2]. However, considering the beam intensities in this region, we have focused on fp shell nuclei (\(^{50}\)Ni and \(^{52}\)Fe).

The measurement was performed at GANIL with radioactive beams produced by fragmentation of a 75A MeV \(^{58}\)Ni beam on a 185 mg/cm\(^2\) Be target purified by the LISE spectrometer. An efficient set-up based on the coupling of the MUST2 and TIARA Silicon arrays for charged particle detection with the EXOGAM gamma-ray detector was used.

Measuring both \(^{52}\)Fe (N=Z=26) which is a partially occupied 0f\(_{7/2}\) shell nucleus and \(^{50}\)Ni (N=Z=28) which has a fully occupied 0f\(_{7/2}\) shell allowed us to study np pairing along the f\(_{7/2}\) shell and to draw conclusions with respect to the previous studies in the sd-shell. Results on the nature of the n-p pairing will be discussed based on the relative intensities of the 0\(^+\) and 1\(^+\) states populated in the \(^{50}\)Ni(\(^{3}\)He)\(^{54}\)Co and \(^{52}\)Fe(\(^{3}\)He)\(^{50}\)Mn reactions and on the angular distributions compared with DWBA calculations.

**References:**


**Direct Detection of the Elusive $^{229m}$Th Isomer: Milestone Towards a Nuclear Clock**

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The isomeric first excited state of $^{229m}$Th possesses the lowest excitation energy of all known nuclei. Its energy has been predicted to be 7.6 eV [1] and could in principle allow to populate this isomeric state with state-of-the-art lasers. This has led to multitude of proposed applications, the best known therein is a nuclear optical clock that could outperform today’s existing atomic optical clocks. However, progress has so far been hindered by the vague and indirect knowledge of the transition energy and lifetime of the isomeric state. The isomer decays via several decay channels to its ground state, whose strength depends on the electron environment of the nucleus: internal conversion (IC) decay occurs as soon as the binding energy of an electron in the surrounding of the nucleus is below the energy of the isomer. Other decay channels are regular $\gamma$ decay or bound internal conversion, where a bound electronic state is excited.

The measurements that led to the first direct detection of the isomer, as well as recent measurements of the internal conversion decay lifetime of neutral $^{229m}$Th, are presented in the talk:

In our experimental setup, $^{229m}$Th is populated via a 2% decay branch of the $^{233}$U $\alpha$ decay. Therefore a $^{233}$U $\alpha$ recoil source is placed in a buffer gas stopping cell, filled with ultra-pure helium that thermalizes the $^{229m}$Th recoil ions. The ions are extracted in a gas jet into a segmented radio frequency quadrupole (RFQ) that allows for beam cooling and bunch creation. Behind the RFQ, other daughter nuclei from the $^{233}$U decay chain are removed with a quadrupole mass separator and a charge state of the ion can be selected. The $^{229m}$Th ions are then collected directly on an MCP detector that is used for neutralization of the ions and for the subsequent detection of the internal conversion electron emitted during the ground-state decay of the isomer [2]. With the creation of ion bunches with a width of 10 $\mu$s, it was possible to determine the half-life of the internal conversion decay to be 7(1) $\mu$s [3].

This work was supported by DFG (Th956/3-1), by the European Union’s Horizon 2020 research and innovation programme under grant agreement 664732 “nuClock” and by the LMU department of Medical Physics via the Maier-Leibnitz Laboratory.

**References:**

Plenary Monday

Two-proton Radioactivity - A Nuclear Structure Tool Beyond the Drip Line

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Two-proton radioactivity is the latest nuclear decay mode discovered. It consists of the emission of a pair of protons from a nuclear ground state. According to the definition by V. Goldanskii who was the first to discuss this new type of radioactivity extensively, one-proton radioactivity is not allowed to be an open decay channel for two-proton radioactivity (2p) candidates.

In pioneering experiments at GANIL and GSI, this new radioactivity was discovered in 2002 and meanwhile 19Mg, 45Fe, 48Ni and 54Zn are established 2p emitters. These results allowed a detailed comparison with the theoretical models available and showed that, at the level of precision of the experimental data and of the predictive power of the models, nice agreement was obtained.

The latest step in the investigation of 2p radioactivity was the use of time-projection chambers to study the decay dynamics via measurements of the individual proton energies and the relative proton-proton emission angle. A first experiment at GANIL and a high-statistics experiment performed at MSU on 45Fe allowed to gain first insights into the decay characteristics by comparison with a three-body model. Meanwhile 54Zn has also been studied with a TPC at GANIL and 2p radioactivity was confirmed for 54Ni at MSU.

In a recent experiment at the BigRIPS separator of RIKEN, a new 2p emitter, 67Kr, was discovered and its basic decay characteristics have been established, whereas two other 2p radioactivity candidates, 59Ge and 63Se, have been shown to decay by beta decay. The decay characteristics of 67Kr are in disagreement with established models and might be a hint for a different decay mode.

The talk will quickly review the experimental status and present in more detail the new results. Future studies of new 2p emitters will also be discussed.

Plenary Monday

First Spectroscopy in 40Mg

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40Mg, with 12 protons and 28 neutrons, lies at the edge of the neutron drip-line and at the intersection of two established regions of nuclear deformation. It is the heaviest Mg isotope experimental accessible today. With the observed collapse of the N=28 neutron shell closure below 48Ca, 40Mg is expected to have a large static prolate deformation, and extends the “peninsula” of deformation reaching from N=20 to 28 in the Mg isotopes. In addition, valence neutrons are expected to occupy the low-l 1p3/2 state, and it is possible that the picture of 40Mg could be one of a well-deformed core surrounded by a neutron halo. With the convergence of effects relating to collective nuclear motion, single-particle effects, and potentially weak-binding, the structure of 40Mg provides a rare and important benchmark for nuclear theories extending to the dripline.

I will present first spectroscopic results for 40Mg, populated following one proton knockout from a secondary radioactive ion beam of 41Al at RIBF, and using the DALI2 gamma-ray detector.
Plenary Monday

Exotic Neutron-rich Medium-mass Nuclei with Realistic Nuclear Force

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The nuclear shell model provides a successful and unified description of both stable and unstable nuclei. Especially for the unstable nuclei, experimental information is less abundant than for stable ones, theoretical challenges play an ever increasing role.

In this work, we will first report on the physics in so-called “island of inversion” with the model space of the sd+pf shell, and then move to the description of the shell structure of N=28,32,34 and 40 with the model space of pf+sdg shell.

In both cases, it is crucial that the newly developed extended Kuo-Krenciglowa (EKK) theory of effective nucleon-nucleon interaction enables us to derive an interaction suitable for several major shells (sd + pf or pf + sdg in this case), unlike conventional Kuo-Krenciglowa (KK) theory.

In the first half of this talk, we will present such an application to the island of inversion, including the cases where conventional approaches with fitted interactions encounter difficulties. By using such an effective interaction obtained from the Entem-Machleidt QCD-based \( \chi N^3LO \) interaction and the Fujita-Miyazawa three-body force, the energies, E2 properties, and spectroscopic factors of low-lying states of neutron-rich Ne, Mg, and Si isotopes are nicely described, as the first shell-model description of the “island of inversion” without fit of the interaction. The long-standing question as to how particle-hole excitations occur across the sd-pf magic gap is clarified with distinct differences from the conventional approaches. The shell evolution is shown to appear similarly to earlier studies.

In the second half, we need to incorporate the effective interaction for pf + sdg shell at least, to describe N=28,32,34 and 40 magic numbers in a unified manner. Starting from a fundamental nuclear force has a great advantage in this case, because too few experimental data are available to fit two-body matrix elements in such a large model space. We will present results of a large-scale calculation on Ca, Ti, Cr, Fe and Ni isotopes with a wide range of neutron number.

Plenary Tuesday

Recent Highlights From the Shores of the Island of Stability

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The hunt for heavy element reached so far proton number 118. In 2016, the IUPAC/IUPAP Joined Working Party validated the discovery of the elements with the proton number 113,115, 117, and 118. Thus, these elements were named and received their place in the periodic table.

Besides the search for new elements, the studies of the basic properties of the heaviest elements are of interest for nuclear physics, atomic physic and chemistry. New and improved experimental techniques provided excess to these properties. I will give an overview on the latest research highlights and a personal view on the future of the research field of the heaviest elements.
**Plenary Tuesday**

**Laser Spectroscopy of the Heaviest Elements**

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The study of the hyperfine structure and the isotope shifts of spectral lines enables properties of atomic nuclei to be obtained in a comprehensive and nuclear model-independent way. These properties include the spin, magnetic dipole and electric quadrupole moments, and changes in the mean-square charge radii. Hence, the establishment of such optical studies in the region of deformed nuclei around nobelium-254 would inevitably attract a high level of interest of both, nuclear physics and atomic physics communities. For atomic physics, for instance, already the observation of atomic transitions in these very heavy elements would provide a stringent test of atomic theories and models addressing relativistic and quantum electrodynamic effects. These studies, however, stagnated for many years at the element fermium for which weighable samples can still be obtained. Elements beyond fermium are challenging in this respect as they are solely produced in nuclear fusion reactions, best at rates of a few atoms per second when utilizing powerful particle accelerators. Only recently successful laser spectroscopy of nobelium in single atom-at-a-time quantities was reported [M. Laatiaoui et al., Nature, 538 (2016) 495]. Several atomic transitions in nobelium-254 were observed and characterized for the first time, providing valuable data and a powerful benchmark for atomic modelling.

To this end, the so-called RAdiation Detected Resonance Ionization Spectroscopy (RADRIS) technique was employed. The fusion products of interest were separated from the primary beam and thermalized in a buffer-gas stopping cell. Those remaining in a positive charged state were accumulated on a catcher filament. Then, the accumulated atoms were evaporated from the filament, ionized in a two-step photoionization process by pulsed lasers and finally guided by suitable electric fields to a silicon detector where they were unambiguously identified via their unique radioactive decay fingerprint.

The investigations were extended to the isotopes nobelium-253 and nobelium-252, which were produced at even lower rates than nobelium-254. Moreover, first steps towards laser spectroscopy of lawrencium-255 were initiated. In my talk, I will highlight the recent findings and give prospects for high-precision measurements using the in-jet laser ionization spectroscopy [R. Ferrer et al., accepted to Nat. Commun.] capable of resolving nuclear isomerism in atomic spectra of these heaviest radionuclides.

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**Plenary Tuesday**

**Superheavy Element Studies at LBNL**

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Despite knowing about SHE for more than a decade, several important questions about these nuclei remain unanswered, including what are the atomic numbers, Z, and masses of these nuclei. Recently, our group has been working towards answering this intriguing question through one of three methods: (i) linking the SHE to known nuclides (ii) Z identification through observation of characteristic x-rays (iii) mass determination through mass analysis. This talk will review the progress that has been made for each of the three methods at LBNL and discuss possible avenues for the future.

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**Plenary Tuesday**

**Influence of Fission on the Prospects for Discovering the Next New Element**

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The four elements that were officially named most recently were all discovered in so-called “warm fusion” reactions, where compound nuclei with excitation energies of ~40 MeV are produced. The key to these experiments has been the use of neutron-rich 48Ca projectiles, which produce nearly spherical compound nuclei when reacting with actinide targets. The relatively neutron-rich compound nuclei have relatively low neutron binding energies and relatively high probabilities of survival against fission. However, more recent experiments to produce new elements using heavier projectiles have not been successful. The cross sections for all of these reactions are extremely small, so recent work at Texas A&M University has studied the reactions of similar projectiles with lanthanide rather than actinide targets. Systematic variation of the projectile and target have allowed for variation of the capture cross section as well as the difference in neutron binding energy and fission barrier height. Excitation functions for the xn and pxn exit channels of a large number of projectile/target combinations have been measured using the MARS spectrometer. A simple theoretical model has been developed that allows for the estimation of the fission and particle emission probabilities from the compound nuclei. It adequately describes the cross sections of 48Ca-induced reactions using only the fission and neutron emission widths, but describing the cross sections of reactions induced by 44Ca and 45Sc projectiles requires the inclusion of the proton and alpha emission widths. Collective effects have been found to be significant, and are needed for accurate description of the cross sections. These results suggest that the discovery of new elements will largely be controlled by the ability of the compound nucleus to survive against fission. This talk will summarize the previous work, the most recent results using 40Ar and 44Ca projectiles, and the theoretical model. Additional remarks will be made on the prospect of using radioactive beams for heavy element synthesis.

**Plenary Tuesday**

**Nuclear Structure Studies far from Stability with Gamma-ray Spectroscopy**

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Far from the valley of beta stability, the nuclear shell structure undergoes important and substantial modifications. In medium-light nuclei, interesting changes have been observed such as the appearance of new magic numbers, and the development of new regions of deformation around nucleon numbers that are magic near stability. The observed changes help to shed light on specific terms of the effective nucleon-nucleon interaction and to improve our knowledge of the nuclear structure evolution towards the drip lines. In the last years, particular effort has been put from both the experimental and theoretical sides on the study of neutron-rich nuclei where these effects manifest more dramatically and their evolution can be followed along the isotopic and isotonic chains. Very interesting results have been obtained in proton-rich nuclei and in particular along the N=Z line. The most precise tool to study the excited nuclear states and their decay properties is high-resolution gamma-ray spectroscopy. Detailed nuclear structure information is becoming available with stable and radioactive beams by means of large gamma-ray spectrometers coupled to key complementary instrumentation that increases the selective power. A review of the recent experimental findings will be presented together with their theoretical interpretation.
Plenary Tuesday

Extending the Reach of ab Initio Nuclear Theory

Dr. STROBERG, Ragnar ¹; Prof. BOGNER, Scott ²; Prof. ROTH, Robert ³; Prof. SCHWENK, Achim ⁴; Mr. SIMONIS, Johannes ³; Ms. STUMPF, Christina ³; Dr. CALCI, Angelo ¹; Dr. HAGEN, Gaute ⁵; HERBERT, Heiko ⁶; Dr. HOLT, Jason ⁴; Dr. MORRIS, Titus ⁷; Dr. NAVRATIL, Petr ⁴; PAPENBROCK, Thomas ⁷; Mr. PARZUCHOWSKI, Nathan ⁸

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A major goal of modern nuclear structure theory is to produce calculations with meaningful uncertainty estimates. Achieving this goal requires ab initio many-body methods which can employ realistic nuclear interactions and solve the Schrodinger equation with reliable precision. The past decade has witnessed a tremendous growth in the range of applicability of ab initio many-body methods, first in light nuclei, then to medium-mass closed shells, one or two particles or holes on top of closed-shells, and ground states of even-even nuclei. I will discuss recent developments in the valence-space in-medium similarity renormalization group method, which enable ab initio treatment of ground and excited states of essentially all nuclei up to mass number A~100.

Plenary Tuesday

Observations at the Outskirts of the Nuclear Landscape - Few Body Open Quantum Systems

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Plenary Tuesday

Gamow-Teller Giant Resonances in $^{132}$Sn

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The Gamow-Teller (GT) transition is one of the most basic excitation modes in nuclei, exhibiting a strong and highly repulsive collectivity as the so-called GT giant resonance (GTGR). The study of the GTGR is an essential step to elucidate the nuclear interactions and structures underlying the collectivity as well as to construct the nuclear models that can reliably describe phenomena whose behaviours are governed by nuclear spin-isospin responses such as weak-interaction processes in astrophysical sites and double beta decay nuclei. Despite of the importance of the GTGR, the existing data are only limited to stable nuclei and there have been no data in nuclei far from the stability line. In this talk, the first experimental determination of the GT transition strength from $^{132}$Sn to $^{132}$Sb, performed using the (p,n) reaction at RIKEN RIBF, will be presented with answers on the questions such as "the spin-isospin collectivity can be different, if one goes far from the stability line?", "most sophisticated nuclear models could reproduce the data". The speaker will also give an overview of the GT studies on nuclei that will be emerging at RIKEN RIBF in the near future.

Breakout A1

Shape Coexistence in Gold, Mercury and Bismuth Isotopes Studied by In-source Laser Spectroscopy at RILIS-ISOLDE

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The competition between spherical and deformed configurations at low energy gives rise to shape coexistence in the neutron-deficient isotopes around Z~82 and N~104 [1]. Along the isotope chain of a number of elements this leads to an abrupt change in the mean-square charge radius of the nuclear ground state when entering the neutron-deficient region. The most notorious case is the shape staggering in the Hg isotopes [2]. An extended experimental campaign to study the mean-square charge radii of the ground and isomeric states of these nuclides, and thereby investigating such regions of nuclear shape changes, is being conducted at ISOLDE by the RILIS-Windmill-ISOLTRAP collaboration. The measurements rely on the high sensitivity achieved by combining in-source laser resonance ionization spectroscopy, ISOLDE mass separation, the Windmill spectroscopy setup [3] and the Multi-Reflection Time-of-Flight (MR-ToF) mass separation technique [4]. In this contribution, we will present the systematics of charge radii and electromagnetic moments recently obtained at ISOLDE for the long isotopic chains of gold (IS534), mercury (IS598) and bismuth isotopes (IS608). For the lightest Au isotopes, a persistence of the strong deformation up to $^{180}$Au was demonstrated for the first time, followed by what we call a ‘jump back to sphericity’, whereby $^{176,177,179}$Au possess much lower deformation compared with strongly deformed $^{180-186}$Au. For the Hg chain, a termination of shape staggering and transition to more spherical shapes in the lightest $^{177,180}$Hg isotopes were deduced. A large odd-even shape staggering at $^{187-189}$Bi, similar to the well-known staggering in the Hg isotopes, was observed at the same neutron number. These three chains clearly demonstrate striking similarities in the shape staggering and shape changes when approaching the neutron mid-shell at N=104, while the lightest gold and mercury chains show the strong tendency towards the smooth nearly-spherical behavior. The data will be compared to mean-field based calculations and discussed within a generic shell-model approach for shape coexistence.

References:

Breakout A1

Charge radii of neutron-deficient $^{52,53}$Fe produced by projectile fragmentation

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A kink at a nucleon shell closure in mean-square charge radii $\langle r^2 \rangle$ along an isotopic chain is a distinct feature of charge radii [1], though the underlying mechanism still remains elusive. Such a feature is clearly visible in the Ca chain at the N = 28 neutron shell closure, which has been a major challenge for nuclear theory to understand [2]. In the present study, the $\langle r^2 \rangle$ of $^{52,53}$Fe below N = 28 were determined [3] to investigate how the pattern of $\langle r^2 \rangle$ around N = 28 changes when moving from semi-magic Ca to Fe isotopes, where the neutron-proton polarization effects are enhanced.

The $^{52,53}$Fe beams were produced by fragmentation of a 160-MeV/nucleon $^{58}$Ni beam in a Be target at NSCL at MSU. The $^{52}$Fe or $^{53}$Fe beams were selected using the A1900 fragment separator [4], thermalized in a gas stopper [5], and extracted at an energy of 30 keV. The Fe$^+$ beam was then transported to the BECOLA facility [6] and bunched-beam collinear laser spectroscopy was performed to measure atomic hyperfine structures (hfs).

Ion beams of the transition-metal Fe are known to be notoriously difficult to produce at ISOL facilities due to long release times from thick targets. The novel scheme of in-flight separation followed by gas stopping was used in the present study for the first time for laser spectroscopy. This is a major step forward and complements such capabilities well established at ISOL facilities, where significant data on $\langle r^2 \rangle$ have been obtained for selective elements [1].

The $\langle r^2 \rangle$ of $^{52,53}$Fe were determined from the isotope shifts of the hfs. The multi-configuration Dirac-Fock method was used to calculate atomic factors. The obtained $\langle r^2 \rangle$ of Fe exhibits a sharp kink at N = 28, which appears to have a similar structure to the Ca chain. The nuclear density functional theory was used to interpret the results. The underlying mechanisms of the kinks in $\langle r^2 \rangle$ of Fe and Ca, as well as the experimental details, will be discussed.

This work was supported in part by the NSF, the U.S. DOE, the German RF, the German MST, the Russian SF and the Russian FBR.

Electron elastic scattering is a simple but very powerful tool to investigate the detailed internal structures of nuclei since it can measure the precise charge density distribution through the well-known electromagnetic interaction. Although the charge density distributions have been already measured for many stable nuclei by former electron scattering experiments, the method has yet to be applied to short-lived RIs since it has been technically difficult to realize a high luminosity (> 10^27 cm^{-2}s^{-1}) for electron-RI scattering to complete the measurement within a reasonable experiment period of time. SCRIT (Self-Confining RI Ion Target) method is a novel and unique technique to realize such a high luminosity of the electron-RI scattering by trapping RI targets 3-dimensionally inside an electron storage ring (SR2) with a barrier potential applied by a SCRIT device and the electron beam potential itself. Following the success of the feasibility test of the SCRIT method, the construction of the SCRIT facility at RIKEN RIBF building has begun in 2008. The SCRIT facility consists of the SR2 with the SCRIT device, an ISOL system called ERIS (Electron-driven RI separator for SCRIT) which utilizes the photo-fission process of uranium to produce RIs, a race-track microtron which provides 150MeV electron beams to the SR2 and the ERIS, and SCRIT detectors to measure the angular cross-section of scattered electrons. At the SCRIT detectors, the angular distribution of scattered electrons is measured by WiSES (Window-frame Spectrometer for Electron Scattering), and the absolute luminosity of electron-RI scattering is obtained from the bremsstrahlung photons measured by LMon (Luminosity Monitor).

After a decade of developments, the SCRIT facility has finally come to the stage of physics experiment. In 2015-2016 the first physics experiment has been performed using stable ^{132}Xe and ^{208}Pb targets with the electron beam energy of 150-300MeV. The SCRIT device has achieved a luminosity above 1027 cm^{-2}s^{-1}, and angular cross-sections of elastically scattered electrons have successfully been measured by the SCRIT detectors. In this contribution, we will present the results of the first physics experiment with ^{132}Xe and ^{208}Pb targets as well as the performances of the SCRIT device and detectors, then discuss some technical difficulties and on-going developments aiming at the world first electron scattering experiment with short-lived RI targets.
About Possible Ambiguities From Alpha Spectroscopy and Direct Mass Measurements of Neutron-deficient Actinium and Radium Isotopes

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Due to the two-body nature of the alpha decay, nuclear alpha spectroscopy has become one of the most relied upon techniques for accurate linking of nuclear masses. Based on a single nucleus of well-known mass serving as anchor point, masses of all mother and daughter nuclei that possess an alpha-decay channel can be determined precisely by the energy of the emitted alpha particles and, if present, subsequent gamma rays. However, the evaluation of masses from spectroscopic data can be influenced by presently unknown (especially low-lying) states in the alpha-daughters and also from complicated spectra that include a large number of isotopes at the same time. In such cases as, e.g., 156 Ho in the 1990’s [1], direct mass measurements with high precision are desired for clarification. At the gas-filled recoil ion separator GARIS-II behind the RILAC accelerator at the RIKEN, the nuclides 210-214Ac have been produced by 169Tm(48Ca,xn)217-xAc and 210-214Ra by 169Tm(48Ca,pxn)217-xRa reactions. Direct mass measurements of these isotopes have so far been carried out only for 211,214Ra [2,3] by Penning-trap mass spectrometry at ISOLDE/CERN. The other isotopes have been investigated by alpha spectroscopy from the 1960’s on (see e.g. [4]) and more recently by alpha-gamma coincidence measurements performed at GSI (see e.g. [5,6]). Direct mass measurements of the eight simultaneously produced isotopes have been performed using a multi-reflection time-of-flight mass spectrograph (MRTOF-MS) coupled to GARIS-II [7]. In this contribution the experimental results, which include six new direct mass measurements, will be presented. Among the new measurements, the existing data in a somewhat wider region of neutron-deficient heavy isotopes and possible future impact of direct mass measurements will be discussed in the context of the significant energy scales of collective effects in heavy nuclei.

References:
Determining Quasifission Time-scales in Superheavy Element Formation Reactions

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Quasifission competes strongly with fusion in reactions forming superheavy elements. The heaviest element that in practice can be created using a 48Ca beam is Z=118 (Oganesson), which has recently been formally approved and named. To form still heavier elements by fusion, use of heavier projectiles is necessary. In general it is understood that heavier projectiles such as 50Ti, 54Cr, 64Ni give lower yields of heavy elements than does 48Ca. In cold fusion, this seems to be associated with the magicity as well as the neutron-richness of 48Ca. Evidence is seen in both evaporation residue cross sections and fission characteristics.

In the case of actinide (hot fusion) collisions, it is not clear whether it is the neutron-richness and low Z of 48Ca that has led to the successful synthesis of superheavy elements from 112 to 118, or whether its doubly-magic property is also critical. It is important to understand this question to reliably predict cross sections for reactions to create new superheavy elements in future.

To address this issue, measurements of quasifission mass-angle distributions have been carried out very recently at the Australian National University. Projectiles of 48Ca, 50Ti, 54Cr, 58Fe and 64Ni bombarded (radioactive) targets of 249Cf, 248Cm, 244Pu, 238U and 232Th respectively. Fusion in each reaction forms Z=118 compound nuclei with similar masses A from 296 to 298. Beam energies from below-barrier to above-barrier have been measured. With an enhanced MWPC detector setup allowing c.m. angular coverage from 20 to 160 degrees, these new mass and angle data reveal the difference in the typical reaction timescale, and the associated mass evolution dynamics in these reactions. This new information is complementary to previous fission mass-energy distribution measurements, and throws light on the difference between cold fusion and hot fusion reaction dynamics.
Breakout A1

First Direct Mass Measurements on Mendelevium with an MRTOF Mass Spectrograph

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Precision mass measurements of unstable nuclei, providing direct measure of the nuclear binding energy, are invaluable for nuclear structure study and have potential for particle identification of atomic nuclide by the precision mass value. For trans-fermium nuclei, of importance for understanding the shell evolution in heavy nuclear system to inspect mass models toward so-called island of stability and the unique identification during new elements search, the mass measurements require fast measurement time even for such a heavy mass nuclei and high efficiency to tolerate extremely low production yields.

Direct mass measurements of trans-fermium nuclei were, so far, performed for only 6 nuclei of nobelium and lawrencium with the Penning trap mass spectrometer SHIPTRAP [1,2]. Recently we implemented a multi-reflection time-of-flight mass spectrograph (MRTOF-MS) located after a cryogenic helium gas cell coupled with the gas-filled recoil ion separator GARIS-II [3] and performed direct mass measurements of mendelevium isotopes for the first time. Using 48Ca beam on natTl target, we produced 249-251Md by fusion-evaporation reaction and successfully measured those masses including new masses of 249-250Md with sub-ppm precision. They were extracted as doubly charged atomic ions from the gas cell as well as other actinides such as nobelium and fermium. Combined with known alpha decay Q-value of 249-250Md, we could newly determine masses of isotopes on the decay chain from bohrium to berkelium.

References:
Breakout A1

Experiments Synthesizing Super-heavy Fl and Og Isotopes with Target Materials From ORNL Irradiated at JINR, Dubna

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More than 50 super-heavy nuclei, which have been identified in fusion-evaporation reactions between 48Ca beams and actinide targets [1,2], form what is known as the ‘Hot Fusion Island’ - a part of the Island of Stability. Most of these nuclei have been discovered in experiments at the Dubna Gas Filled Recoil Separator (DGFRS), using actinide target materials produced at Oak Ridge National Laboratory [3]. These studies have been recently augmented by using a new highly segmented Si detector and digital detection system [4,5] commissioned by the ORNL-UTK team and implemented at the DGFRS. The system has robust analysis capabilities, especially for very short lived activities, and detection efficiency at high beam rate.

The utility of this new system will be detailed by discussing the observation of heavy and super-heavy recoils and the subsequent alpha and/or spontaneous fission radiations. The measurement of several Th activities from the 48Ca + natYb calibration reaction will be shown including activities on the order of 1 μs. Spontaneous fission and alpha decay of heavy implants observed during irradiations of Pu and Cf targets will be shown.

This includes the discovery of a new Flerovium isotope [5], recent observations of 294Og, as well as details of the experiment running through February 2017 which may attempt to synthesize a chain of alpha activities which would connect the ‘Hot Fusion Island’ to the ‘Nuclear Mainland’.

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Breakout A1

The New Isotopes $^{240}$Es and $^{236}$Bk

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The neutron-deficient $^{240}$Es nucleus was synthesized for the first time using the fusion-evaporation reaction $^{209}$Bi($^{34}$S, 3n)$^{240}$Es at the Accelerator Laboratory of University of Jyväskylä (JYFL), Finland. The gas-filled recoil separator RITU [1] was used to separate the fusion-evaporation products from the primary and scattered beam. The radioactive decays originating from $^{240}$Es and its daughters, including the hitherto unknown $^{236}$Bk, were measured with the focal plane spectrometer GREAT [2]. Identification of $^{240}$Es was made on the basis of recoil-alpha-alpha correlated chains ending with the known granddaughter $^{236}$Cm. A significantly high electron-capture delayed fission (ECDF) probability was measured for $^{240}$Es [3]. The new isotope $^{236}$Bk that was populated in the alpha decay of $^{240}$Es was identified by its ECDF branch [3]. These new data show a continuation of the exponential increase of ECDF probabilities in more neutron-deficient isotopes. The results on the decay properties of $^{240}$Es and $^{236}$Bk together with the data analysis will be presented.

References:
Understanding the Nature of the Low-energy Enhancement in the Photon Strength Function of $^{56}$Fe

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The recent discovery of the low-energy enhancement in the photon strength function (PSF) of medium mass nuclei in the Fe and Mo region [1] has attracted great experimental and theoretical attention, as it may represent a new decay-mode [2]. The presence of an enhanced decay probability of low-energy gammas below the neutron threshold has the potential to greatly affect a broad range of applications including the astrophysical r-process and nuclear reactors [3-4]. Recent shell model calculations on $^{94}$Mo, $^{95}$Mo and $^{90}$Zr show that the enhancement could be due to a large B(M1) strength for low energy gamma-rays caused by orbital angular momentum recoupling of high-j orbits [5], while other mechanisms suggest an enhanced E1 strength [6].

A recent experiment designed to confirm the multipolarity and determine the electric or magnetic character of transitions in the region of the PSF enhancement in $^{56}$Fe was performed at ATLAS/ANL using GRETINA and the Phoswich Wall [7]. A 16 MeV proton beam was used to inelastically excite a $^{56}$Fe target to the quasicontinuum where it promptly decayed by gamma-ray emission. The PSF can be extracted using two-step cascades from the quasicontinuum to specific low-lying levels by a model independent method first employed in $^{95}$Mo [8]. This method is being extended to take advantage of GRETINA as a polarimeter to obtain angular and polarization information in the region of the low-energy enhancement of the PSF. Preliminary results will be discussed.

References:


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Advances in Radioactive Isotope Science / Book of abstracts

**Breakout B1**

**Investigation of $^{198}$Hg and $^{199}$Hg Through Direct Reactions for the Interpretation of EDM Limits**

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The observation of a large permanent electric dipole moment (EDM) would represent a clear signal of CP violation from new physics outside the Standard Model. The $^{199}$Hg isotope currently provides the most stringent limit on an atomic EDM, which is converted to a limit on the nuclear EDM via a calculation of the Schiff moment. To do this knowledge of the nuclear structure of $^{199}$Hg is required. Ideal information to further develop and constrain the $^{199}$Hg Schiff moment nuclear structure theoretical models are the E3 and E1 strength distributions to the ground state, and E2 transitions amongst excited states. The high level density of $^{199}$Hg makes those determinations extremely challenging, however similar information can be obtained from exploring surrounding even-even Hg isotopes. One of the most direct ways of measuring the E3 and E2 matrix elements is through inelastic hadron scattering, and single-nucleon transfer reactions on targets of even-even isotopes of Hg can yield important information on the single-particle nature of $^{199}$Hg.

As part of a campaign to study the Hg isotopes, a number of experiments have been performed using the Q3D spectrograph at the Maier-Leibnitz Laboratory, with 22 MeV deuteron beams impinging on enriched Hg$^{32}$S targets. The first experiment accesses the E2 and E3 matrix elements in $^{198}$Hg via inelastic deuteron scattering. We measured 9 angles ranging from 10 to 115 degrees up to an excitation energy of 5 MeV. The second set of measurements discussed will be single-nucleon transfer reactions, $^{198}$Hg(d,p)$^{199}$Hg with spin-parity assignments and spectroscopic factors extracted through distorted-wave Born approximation calculations with global optical model parameter sets.

**Breakout B1**

**Ba-ion Extraction From High Pressure Xe Gas for Double-beta Decay Studies with nEXO**

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An RF-only ion funnel has been developed to efficiently extract single Ba ions from a high-pressure (10 bar) xenon gas into vacuum. Gas is injected into the funnel where ions are radially confined by an RF field while the neutral gas escapes. Residual gas flow alone (without any DC drag potential) transports the ions longitudinally through the funnel. In the downstream chamber the ions are captured by a sextupole ion guide and delivered to an ion detector. The xenon gas is captured by a cryopump and then recovered back into storage cylinders for future use.

With the current setup ions were extracted from xenon gas of up to 10 bar and argon gas of up to 7.8 bar. These are the highest gas pressures ions have been extracted from so far. The ions were produced by a Gd-148 driven Ba-ion source or a Cf-252 fission source placed in the high pressure gas. The ion transmission has been studied in detail for various operating parameters. A mass spectrometer has been used for mass-to-charge identification of the extracted ions. This identification is being improved to further investigate the properties of the funnel and to measure the Ba-ion extraction efficiency of this setup. This approach of ion extraction is intended for application in a future large-scale Xe-136 neutrinoless double-beta decay ($0\nu\beta\beta$) experiment. The technique aims to extract the $\beta\beta$-decay product, Ba-136, from the xenon gas and detect it unambiguously and efficiently. This individual identification of the decay product allows for an ideally background-free measurement of $0\nu\beta\beta$ by vetoing naturally occurring backgrounds. This identification enables a higher level of sensitivity to the $0\nu\beta\beta$ decay half-life and thus is a more sensitive probe of the nature of the neutrino.
Nuclei far from stability with a large imbalance between the number of protons and neutrons exhibit characteristic decay modes which are still far from being fully explored, both experimentally and theoretically [1]. One of them is emission of beta-delayed charged particles, which occurs for nuclei close to the proton drip-line. In addition to single (beta p) and double (beta 2p) delayed protons known since long, other channels, like the recently observed delayed emission of three protons (beta3p) become important. Delayed emission of charged particles has been also observed for very neutron-rich nuclei. Good understanding of such decays is necessary when the correct knowledge of beta strength distribution is demanded.

Experimental investigations of exotic and rare decay channels require special instrumentation offering efficiency and sensitivity. An example of such an approach is the Optical Time Projection Chamber (OTPC) developed at the University of Warsaw. Designed with the specific goal to study two-proton radioactivity (2p), it proved to be an excellent tool for investigation of other decay channels accompanied by emission of charged particles. Among interesting results obtained with help of the OTPC, in addition to 2p spectroscopy [2,3], are the first observation of the beta 3p decay mode in three nuclei [4,5,6], a study of 6He decay into the alpha + d continuum [7], and a measurement of beta-delayed tritons from 9He [8]. In the talk I will give a short overview of the charged-particle spectroscopy of exotic and rare decay channels investigated with help of the OTPC detector. In more detail I will discuss the decays of 6He and 8He, as well as the most recent results obtained for decays of 26P and 27S. At the end I will sketch some ideas for future studies, including an ambitious search for beta-delayed protons emitted by 11Be.

References:
[8] S. Mianowski et al., to be published.
Breakout B2

Excursion Far Beyond the Proton Dripline Along Ar and Cl Isotopes

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Nuclei beyond the proton drip line have been intensively investigated in recent years, and their structure exhibited exotic features that cannot be found in particle-stable nuclei. For instance, two-proton (2p) radioactivity of elements was discovered on ⁴⁵Fe. In spite of the experimental advances, most 2p-decay precursors remain unexploited though their low-excitation spectrum is expected to be discrete. This naturally causes the question: How far beyond the driplines are the nuclear structure phenomena fade and are completely replaced by continuum dynamics?

In this talk, the first spectroscopic studies of the chains of 2p emitters ³¹,³³,³⁰Ar and their 1p-unbound subsystems ³⁰,³⁹,³⁵Cl will be reported. The corresponding experiment is based on measurements of in-flight decays of the 2p emitters and tracking trajectories of their decay products by microstrip silicon detectors [1].

The lowest states in ³⁰Ar and ³⁹Cl point to a violation of isobaric symmetry in the structure of these unbound nuclei (i.e., the Thomas-Ehrmann shift). The 2p decay has been identified in a transition region between simultaneous 2p and sequential proton emissions from the ³⁰Ar ground state, which is characterized by interplay of three-body and two-body decay mechanisms. Such a phenomenon, never observed before, is argued to be common in 2p-unbound nuclei and could be of interest for other disciplines dealing with few-body systems [2]. The spotted dramatic change of odd-even mass staggering in 2p-unbound nuclei calls for further systematic investigation.

Systematic studies of the ground and excited states of unbound Ar and Cl isotopes have revealed that the Thomas-Ehrmann shifts are even larger for the ²⁹Ar and ²⁸Cl isotopes in comparison with ³⁰Ar and ³⁹Cl, respectively. Predictions for even more remote isotopes ²⁸Ar and ²⁷Cl are provided by using the elaborated models. For these isotopes, the Thomas-Ehrmann effect is expected to be less important, as their isobaric mirror partners are located near the neutron drip line.


Breakout B2

Study of ⁶⁸Co Low-energy Structure via β Decay

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The N = 40 subshell closure, which arises from the energy separation of the νpf shell and the νgd2 single-particle state, has long been investigated for its impact on nearby neutron-rich nuclei. The fragility of this N = 40 subshell closure is highlighted by the sudden onset of collectivity as protons are removed from the νf7/2 single-particle state. Cross-shell excitations have been used to describe the observation of shape coexistence between spherical and prolate-deformed configurations. Within the neutron-rich odd-A Co isotopes, shape coexistence is supported through the identification of a (1/2⁻) shape isomer found at low energies alongside higher-spin states associated with the normal-order configurations. For ⁶⁸Co, a recent paper on a β-decay study at the National Superconducting Cyclotron Laboratory (NSCL) [1] concluded that the lowest-energy state can be attributed to a deformed configuration, further extending the presence of shape coexistence to this nucleus. This work reports on ⁶⁸Co as determined from the analysis of new data from NSCL utilizing the selectivity of low-spin β decay from ⁶⁸Fe to populate ⁶⁸Co. An expanded description of the low-lying structure of ⁶⁸Co will be presented.

This work was supported in part by the National Science Foundation (NSF) under Contract No. PHY-1102511 (NSCL) and Grant No. PHY-1350234 (CAREER), by the Department of Energy National Nuclear Security Administration (NNSA) under Grant No. DE-NA0002132 and Award No. DE-NA0003221 and through the Nuclear Science and Security Consortium under Award No’s DE-NA0000979 and DE-NA0003180, by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under Contract No. DE-AC-06CH11357 (ANL) and Grant No’s. DE-FG02-94ER40834 (UM) and DE-FG02-96ER40983 (UT), and by the U.S. Army Research Laboratory under Cooperative Agreement W911NF-12-2-0019.
Breakout B1

Shape Coexistence in the $^{78}$Ni Region: Intruder Second 0$^+$ State in $^{80}$Ge

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The coexistence of normal and intruder nuclear states close in energy is a characteristic feature of nuclear structure [1]. The lowering in energy of states originating from excitations across the shell closures is a delicate balance between the energy cost to break the shell gap, and the gain in pairing and quadrupole energy. A region of great interest for these studies is the $N = 50$ isotonic chain, down to $^{78}$Ni. On the one hand, the size and reduction of the $N = 50$ gap in exotic nuclei are a much debated issue, impossible to reproduce with two-body forces from first principles.

On the other hand, the presence of the $g_{9/2}, d_{5/2}, s_{1/2}$ neutron shells across the gap determines a large quadrupole interaction. Therefore, the search for excited 0$^+$ states from two-particle two-hole (2p - 2h) excitations in the region can help to set benchmarks for nuclear models in the region.

The $N = 48$ $^{80}$Ge nucleus was studied by means of beta-delayed electron-conversion spectroscopy at ALTO [2]. The radioactive $^{80}$Ga beam was produced through the ISOL photofission technique and collected on a movable tape for the measurement of and $e^-$ emission following decay. An electric monopole E0 transition which points to an intruder second 0$^+$ state was observed for the first time.

This new 639 keV state is lower than the first 2$^+$ level in $^{80}$Ge (659 keV), and provides evidence of shape coexistence close to $^{78}$Ni. This result will be compared with theoretical estimates, helping to explain the role of monopole and quadrupole forces in the weakening of the $N = 50$ gap at $Z = 32$. The evolution of intruder 0$^+$ states towards $^{78}$Ni will be discussed. It will also be pointed out how these and other findings [3] may hint to a "$s_{1/2}$ physics" in this region, and how this relates to recent measurements of unexpected high-energy gamma radiation following beta decay beyond $N=50$ [3].

References:

Breakout B1

Search for the Neutron Dripline for Fluorine and Neon Isotopes

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Particle-bound isotopes along the neutron dripline have been searched for fluorine ($Z = 9$) and neon ($Z = 10$) isotopes at the RIKEN RI Beam Factory (RIBF) by using projectile fragmentation of an intense $^{48}$Ca beam at 345 MeV/nucleon and the large-acceptance fragment separator BigRIPS. Observation of null counts for $^{32}$F, $^{33}$F and $^{35}$Ne, $^{36}$Ne isotopes and comparison with their expected production yields have showed that existence of particle-stable states of these isotopes is excluded with high confidence levels. It is thus found that the most neutron-rich isotopes $^{33}$F and $^{35}$Ne previously observed are the heaviest of these isotopes. The confirmed neutron driplines have thus been extended for the first time since nearly 20 years ago, in which the $^{24}$O isotope was confirmed to be on the dripline of oxygen ($Z = 8$) isotopes. The present determination of neutron driplines will provide keys to understand the nuclear stability at extremely neutron-rich conditions.
Breakout B1

The AME2016 Atomic Mass Evaluation

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The Atomic Mass Evaluation (AME) has been serving the research community with the most reliable source for comprehensive information related to the atomic masses since 1950s. It provides the best values for the atomic masses and their associated uncertainties by evaluating all available experimental data from nuclear reactions, radioactive decays and direct mass measurements using a weighted, least-squares method approach. The last atomic mass evaluation, AME2012, was published in December 2012 [1,2] and the main aspects of AME2012 have been presented at the last ARIS conference [3]. Since the publication of AME2012, the experimental knowledge of atomic masses has been continuously expanding along two main directions, including: measurements aimed at high-precision mass values and at the most exotic nuclei far from the stability. The AME2016 will be published in March, 2017. At this conference, the AME2016 will be presented and compared with the previous AME2012 evaluation. The impact of new mass measurements will be reviewed and discussed.

References:

Breakout A2

Monopole and Dipole Transitions in Light Nuclei

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Cluster structures have been found in light unstable nuclei as well as stable nuclei. For instance, neutron-rich Be isotopes show remarkable cluster structures of a 2 alpha core with surrounding excess neutrons. For C isotopes, three-body cluster structures in excited states have been suggested and attracting a great interest. How can we experimentally probe such the cluster structures? For the ground states, it is useful tool to measure charge radii along an isotope chain because they reflect the cluster development though the proton distribution. For excited states, monopole and dipole excitations, which are measured by inelastic scatterings, can be useful approaches.

Low-energy isoscalar (IS) and isovector (IV) strengths separated from the giant resonances appear originating in new collective modes such as cluster modes and valence neutron modes, respectively. Our aim is to clarify the natures of low-energy ISM, ISD, IVD strengths and understand the mechanism of the separation of low-energy strengths from the GR strengths. For this aim, we apply a newly-developed method, the shifted base AMD, and combine it with the cluster GCM. The framework can describe the GR modes given by the coherent 1p-1h excitations as well as the large amplitude cluster modes. Applications to $^6$Be and $^{10}$Be and that to $^{12}$C are reported. In $^6$Be and $^{10}$Be, the IVGDR in E > 20 MeV shows a two peak structure because of the dipole excitation in the 2-alpha core with the prolate deformation, whereas the low-energy E1 resonances appear in E < 20 MeV exhausting 20% of the TRK sum rule. The 1- resonance at E~15 MeV in $^{10}$Be has a $^6$He+alpha cluster structure and shows the remarkable E1 strength because of coherent contribution of two valence neutrons. The calculated E1 strengths reasonably describe the experimental photonuclear cross sections. We also investigate the ISM and ISV strengths in $^{12}$C and discuss the remarkable low-energy strengths for cluster states separating from the GR strengths. We show that the monopole and dipole excitations are good probes to pin down the cluster structures in the excited states.
Advances in Radioactive Isotope Science / Book of abstracts

Breakout A2

A Hybrid Configuration Mixing Model for the Low-lying States of Unstable Nuclei

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We have recently introduced a new approach, which is meant to be a step towards complete low-lying spectroscopy of odd-mass nuclei. In the first applications, we have limited ourselves to a magic core plus an extra neutron or proton. The model does not contain any free adjustable parameter, but is based on a Hartree Fock (HF) description of particle states and Random Phase Approximation (RPA) calculations for core excitations: the coupling between these states is treated self-consistently and the resulting Hamiltonian is solved exactly. The model is an extension of previous Particle-Vibration Coupling (PVC) calculations. However, at variance with these, it also includes the coupling with non-collective core excitations and can also describe states of shell-model type like 2 particle-1 hole.

The underlying spirit is of course related to filling the gap between shell model-like approaches for low-lying spectroscopy, and the traditional HF+RPA approach to high-lying states like giant resonances. At present, we apply this model by using Skyrme functionals.

We shall discuss the results for neutron-rich nuclei in the Ca region and around 132Sn. In these cases the agreement with existing experimental data is generally good. We shall also demonstrate the usefulness of such a model for low-lying spectroscopy of more neutron-rich, weakly bound systems.

Breakout A2

Quantifying Uncertainties for Optical Model Parameters and Cross Sections

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While uncertainty quantification has been applied to many fields within nuclear theory, it is still relatively unstudied in reaction theory. There are many sources of these uncertainties, including but not limited to the effective potentials used, model approximations and simplifications, and structure functions. Many of these have been investigated [1], however, they have not been systematically studied. For instance, the uncertainties from optical model parameterizations are often calculated by computing the difference between the cross sections that result from two parameterizations used within the same reaction framework. Although this gives a relative error between the two, it does not give a systematic way to quantify the uncertainty from a given parameterization.

To begin to quantify the uncertainties coming from these optical model parameterizations, chi-square fitting to elastic scattering data is used to constrain the depth, radius, and diffuseness of each term in the optical model potential. From these fits, 95% confidence bands can be constructed around cross-section calculations from the best-fit parameterizations. Correlations between the parameters can also be explored. Correlations within the model itself can be taken into account using a correlated chi-square fitting function, which produces lower chi-square values, larger confidence bands, and a more physical description of the data. We will discuss results from this process as applied to 12C-d elastic scattering and transfer, as well as 45Fe-n elastic and inelastic scattering. [2]

This fitting procedure, however, only explores the parameter space around a given minimum and does not provide a way to include knowledge about the physical constraints on the parameters. As an alternative, a Bayesian analysis can be performed, using a Markov Chain Monte Carlo to explore the parameter space – constrained by the elastic scattering data and physical limits on the optical model parameters. Results from this first exploration will be shown, along with comparisons to the chi-square fitting procedure. Finally, possible future developments will be discussed.

References:


Breakout A2

Time-dependent Description Nuclear Collisions and Infinite Nucleonic Systems

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Time-dependent nuclear density functional theory (TDDFT) is a tool of choice for describing heavy ion collisions. Here we present a study of nuclear focusing on the aspect of nucleonic clustering in the intermediate states. To visualize emergent clusters, we use the nucleonic localization function, which is based on the probability of finding two nuclei with same spin and isospin at a given point. This measure was shown to be an excellent indicator for clustering in time-independent DFT calculations. We show that the TDDFT solutions exhibit strong clustering especially in the collision of light nuclei. The nucleonic localization is also an excellent measure of clustering in time-dependent simulations and gives important insights into the reaction mechanism.

TDDFT can also be used to describe infinite systems such as nuclear pasta, which is present in the inner crust of neutron stars. Here we study the time-dependent modes of nuclear rods. To reduce finite-volume effects, we utilize the twist-averaged boundary conditions (TABC). We show that only with the help of TABC we can extract important information pertaining to the inner crust of neutron stars.

Breakout A2

Challenges in Describing Near-Barrier Fusion: Pinning Down the Interplay of Breakup, Transfer and Fusion

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Understanding the interactions of weakly bound nuclei, and their reaction outcomes, is a key challenge in nuclear reactions research. Apart from the well-known channel coupling effects, reaction dynamics involving weakly-bound nuclei has added complexity due the presence of low-lying particle unbound states, not just in the interacting nuclei but also in neighboring nuclei that are populated following nucleon transfer. Currently there is no theoretical model to describe all the modes of breakup (particularly transfer-triggered breakup) and their effect on fusion. Thus, experimental observations play a crucial role in formulating theoretical models of near-barrier reaction dynamics.

The findings of suppression of above barrier complete fusion, first observed using weakly bound stable beams, and later for light radioactive beams, led to idea that the suppression is caused by breakup of the projectile before reaching the fusion barrier. This idea was tested recently using a large angular acceptance detector array to measure coincident charged fragments following breakup of weakly bound stable beams on a wide range of targets. A recently developed classical model was combined with new experimental observables to separate breakup that occurs in the incoming trajectory from that in the outgoing trajectory. This separation proved crucial as it shows that breakup prior to reaching the barrier is insufficient to explain the observed suppression of complete fusion. Thus some other mechanism must also be contributing to suppression of complete fusion.

These new measurements will be presented and possible mechanisms that can cause reduction in fusion will be discussed. The latter will draw on similarities observed in experiments with well-bound nuclei where transfer to highly excited states is being investigated as a possible doorway to energy dissipation that can reduce complete fusion cross sections. These emerging ideas built on recent experiments serve as pointers to the development of new models.
Breakout A2
Mass Measurements of Neutron-rich Rare-earth Isotopes

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MUMPPOWER, Matthew 7; NYSTROM, Andrew 7; RAY, Dwaipayan 6; Prof. SHARMA, Kumar S. 4; SURMAN, Rebecca 7; VASSH, Nicole 7;
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The rapid neutron capture process (r process) is thought to be responsible for the production of roughly half of the heavy elements found in nature, however the site of the r process is unknown and remains one of the most active areas of research in nuclear astrophysics. Testing r-process predictions requires experimental nuclear data inputs including masses, beta-decay properties, and neutron-capture rates. A recent study [1] has posited a link between the formation of the rare-earth peak near N = 100 and an array of potential r-process sites, but there is currently little available nuclear data in this region. As current RIB facilities improve and next-generation facilities come online, the opportunity to test such r-process calculations and inspire others is quickly growing. One such facility is CARIBU, located at Argonne National Laboratory, where intense beams of neutron-rich isotopes are produced from the spontaneous fission of 252Cf. The recent commissioning of a MR-TOF at CARIBU provides highly mass-resolved (R>50,000) beams to the low-energy experimental area where the Canadian Penning Trap mass spectrometer (CPT) is housed. A major upgrade to the detector system at the CPT has been made in order to implement the contemporary Phase-Imaging Ion-Cyclotron-Resonance (PI-ICR) mass measurement technique [2], which has allowed us to probe further from stability than was previously possible. PI-ICR is intrinsically more efficient than other Penning trap mass measurement schemes and offers increased sensitivity to more weakly produced isotopes without loss in precision. Buoyed by the MR-TOF, this new technique has been used to determine the masses of a number of previously unmeasured rare-earth nuclides around A~160 in the past year. The benefits of PI-ICR and the astrophysical implications of the newly measured masses will be discussed.


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Breakout A2
Precision Mass Measurements of Neutron-rich In isotopes Relevant to r-process Calculations

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Mass measurements of nuclei far from stability provide an important input to nuclear structure studies and simulations of the rapid-neutron capture process (r-process), the proposed mechanism by which many of the elements heavier than iron are created. Since the exact astrophysical site of this process is still under debate, the route by which the chain of neutron captures, photodissociations and beta decays proceeds through the nuclear chart is uncertain, and sensitive to the model inputs. Precise neutron separation energies, derived from mass measurements, are particularly important for the calculation of elemental abundances predicted by various r-process scenarios. The TITAN experiment at TRIUMF has recently measured the masses of the ground and isomeric states of the neutron-rich indium isotopes A=125-130 using the time-of-flight ion cyclotron resonance technique in a precision Penning trap. Isotopes near neutron shell closures, such as 125-130In, are particularly important for r-process calculations. At these points, the rate of neutron capture slows, resulting in experimentally observed abundance peaks. The indium isotopes presented here lead up to the N=82 shell closure at 131In, and their mass uncertainties are critical for predictions of the A=130 abundance peak. They also present a significant improvement in precision over previous measurements, from which only 129In/129mIn were well known. This increase in precision will feedback into r-process calculations and mass models, leading to improved future predictions. The significance of these new high-precision mass measurements for elemental abundance predictions will be discussed, as well as the implications for nuclear structure, based on comparisons to theory.
Breakout A2

Informing Neutron Capture on Tin Isotopes in r-process Freeze Out

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About half of the elements heavier than iron are formed in rapid neutron capture, r-process nucleosynthesis. Mumpower, Surman, McLaughlin, and Aprahamian [1] have identified unknown nuclear observables that can significantly impact final abundances and could also help to constrain the site of the r process. One of these observables are neutron capture rates at late times, freeze-out, in an r-process event, in particular on the N<82 isotopes of tin. To determine spectroscopic strengths and inform neutron capture rates, the (d,p) reactions were measured in inverse kinematics with radioactive 126,128,130,132Sn and stable 124Sn beams at the Holifield Radioactive Ion Beam Facility. Reaction protons were measured with SuperORRUBA highly segmented silicon strip detectors. The experimental differential cross sections were analyzed in the Finite-Range ADiabatic Wave Approximation framework [2] with Koning-Delaroche global optical model parameters to deduce neutron spectroscopic factors that were then used to calculate the direct-semi-direct (DSD) neutron capture cross sections with the CUPIDO code [3]. The present DSD cross sections are lower than those calculated by Chiba et al. [4] before the excitation energies and spectroscopic factors of 1/2- and 3/2- states in neutron-rich Sn isotopes had been measured, and significantly lower than the (n,γ) cross sections from statistical processes expected for N<82 tin isotopes. To understand the statistical contribution to the (n,γ) rate requires a valid surrogate and techniques that can exploit radioactive ion beams. The (d,py) reaction has recently been validated as such a surrogate [5] and the Gammasphere-ORRUBA setup [6] is well-suited for such measurements in inverse kinematics. The present talk would present the DSD results for neutron-rich Sn isotopes and the prospects for deducing the statistical component of neutron capture near the r-process path. This work by the ORRUBA collaboration is supported in part by the U.S. Department of Energy and National Science Foundation.

[5] A. Ratkiewicz et al., to be published

Breakout A2

Measurement of 21Na(α,p)24Mg Cross Section for the Study of 44Ti Production in Supernovae

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While core collapse supernovae have long captured the attention of physicists and astronomers, surprisingly little is currently known about the nature of the explosion mechanism. This is due to the complexity of the explosion, the large computational requirements for even 2D simulations, and the lack of precise nuclear physics inputs to these models. One of the few methods by which this explosion mechanism might be studied is through a comparison of the amount of 44Ti observed by space-based γ-ray telescopes and the amount predicted to have been generated during the explosion. For these comparisons between observations and models to be made, however, more precise nuclear physics inputs are required. The reaction 21Na(α,p)24Mg has been identified as one of the key reactions affecting the 44Ti mass fraction by factors of 10 or more. There are currently no published data on this reaction. A direct experimental measurement of the 21Na(α,p)24Mg cross section has been carried out at TRIUMF, Canada. This experiment utilised the TUDA facility at ISAC-I. The 21Na radioactive beam, at high intensity, impinged on a 2cm wide gas target, containing 100 torr of 4He. A downstream silicon array, consisting of a DE-E telescope, detected the reaction protons. An upstream silicon array measured beam back-scattered from an Au foil located at the entrance of the gas target, for normalisation. Data were collected at four laboratory energies covering Ecm=3.2-2.5 MeV, which is approximately the top half of the 2GK Gamow Window. Preliminary analysis results will be presented, along with details of the experimental challenges encountered and the steps taken to overcome them.
Breakout B2

Shape Evolution in Neutron-rich Kr Isotopes Beyond N=60: First Spectroscopy of $^{98,100}$Kr

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Across the nuclear chart, some of the most drastic known shape transitions appear in the A~100 region at N=60 for neutron-rich Zr and Sr isotopes [1,2]. Such a sudden rearrangement of a whole nucleus only adding a couple of nucleons is a peculiar feature of the nuclear system highlighting the subtle interplay between collective and microscopic degrees of freedom. Transitional regions where this phenomenon happens are thus preferential areas to be mapped experimentally. Neutron-rich Kr isotopes are especially interesting in this respect since this sudden increase of collectivity at N=60, like in the Zr and Sr chains, was not observed for $^{96}$Kr [3]. Instead, a smooth reduction of $E(2^+)$ and rise of $B(E2,0^+\rightarrow 2^+)$ excitation strength suggest a gradual development of collectivity. Mass measurements of $^{96}$Kr, and $^{98,100}$Rb isotopes together with charge radii studies also emphasized that this abrupt shape transition at N=60 extends down to Z=37 and not to Z=36 in $^{96}$Kr but could not rule out that such a transition is not shifted to higher neutron numbers [4, 5].

To explore and delineate the boundaries of this nuclear shape transition region [4], we performed the first in-flight $\gamma$-ray spectroscopy of very neutron-rich $^{98,100}$Kr nuclei during the 2015 SEASTAR campaign using (p,2p) direct reactions from $^{99,101}$Rb isotopes at 266 and 257 MeV/u respectively. Thanks to the state-of-the-art combination of the RIBF facility, a 100-mm thick liquid hydrogen target and the MINOS+DALI2 setup, we identified their $2^+$ states but also additional low-lying states in $^{98}$Kr providing the first experimental evidence of the lowering in energy of an excited configuration coexisting with the ground-state one. These new experimental results will be discussed and compared to beyond mean-field calculations [6,7], which link them to the coexistence of oblate and prolate configurations at low energy. Interesting differences on how these configurations are predicted to order and mix around $^{98,100}$Kr will be described since they call for future experimental and theoretical benchmarks in the region.

References:
**Breakout B2**

**Collectivity in the Vicinity of $^{78}$Ni: Coulomb Excitation of Neutron-rich Zn at HIE-ISOLDE**

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Nuclei in the vicinity of $^{78}$Ni have recently been in focus of many experimental and theoretical investigations. In particular, the neutron-rich Zn isotopes, only two protons above the Ni isotopic chain, are ideally suited to study the evolution of the $Z = 28$ proton shell gap, and the stability of the $N = 50$ neutron shell gap. In the last decade, several experiments were performed to study the collectivity in the even-even Zn isotopes between $N=40$ and $N = 50$ [1-4], but their results are not consistent; consequently, the evolution of nuclear structure in the neutron-rich Zn nuclei is not fully understood.

The ISOLDE facility finished in 2016 the first phase of a major upgrade in terms of the energy of post-accelerated exotic beams bringing it up from 3 MeV/u to 5.5 MeV/u. The increased beam energy strongly enhances the probability of multi-step Coulomb excitation, giving experimental access to new excited states and bringing in-depth information on their structure.

The very first HIE-ISOLDE beam experiment in October 2015 and its continuation in 2016 have been dedicated to the study of the evolution of the nuclear structure along the zinc isotopic chain. The preliminary results discriminate between the two experimental values of $B(E2; 4^+ \rightarrow 2^+)$ in $^{74}$Zn, and yield for the first time a $B(E2; 4^+ \rightarrow 2^+)$ value in $^{78}$Zn.

**References:**


**Breakout B2**

**Shape Coexistence in Neutron-rich Odd-mass S Isotopes**

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Collective motions in atomic nuclei such as rotation and vibration have been characterized by the ground-state shape as a single basis. This picture can be altered in exotic nuclei with unusual proton-to-neutron ratios if the nuclear shape changes drastically at low excitation energies. The phenomena of shape coexistence occur when two or more states with distinct shapes exist in a nucleus within a narrow energy range.

Recently there has been an increasing interest for shape coexistence phenomena in neutron-rich S isotopes. Previous studies suggested that the $N=28$ shell gap is weakened in the neutron-rich region inducing strong competition among different configurations as well as fairly large collectivity in $^{40,42,44}$S isotopes. Therefore it is important to address the question as to how shape coexistence manifests itself and persists in neutron-rich odd-mass S isotopes in the vicinity of $N = 28$.

Model-independent lifetime measurements of the $^{43,45}$S excited states were performed by applying the Recoil Distance Method with the TRIPLEX Plunger in conjunction with GRETINA to fast rare isotope beams at the NSCL. We will discuss the search for isomeric or long-lived states in $^{45}$S and attempt to fully characterize the band structure of the low-lying states in $^{45}$S, which provide key information to establish a comprehensive picture of the shape coexistence in this region.
Breakout B2

Collectivity Along \( N=50 \): The Neutron-magic \(^{92}\text{Mo}\) and \(^{94}\text{Ru}\)

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The \(^{100}\text{Sn}\) nucleus, being the heaviest bound doubly-magic nucleus with equal number of protons and neutrons, has attracted considerable interest from the experimental as well as theoretical point of view. In particular, the structure of this nucleus and its neighbours are excellent benchmark cases to test state-of-the-art shell-model calculations in the region.

Such models, predict an inversion of the \(B(E2;4^+\rightarrow 2^+)\) trend towards the complete occupation of the \(g_{9/2}\) orbital - thus towards \(^{100}\text{Sn}\) - owing to an increasing pairing-strength along the \(N=50\) isotones [1], differently to what has been observed for the neutron-rich \(Z=28\) isotopes, where neutrons occupy the same orbitals.

To test experimentally this phenomenon, the AGATA gamma array, installed recently at the GANIL laboratory, has been used, in combination with the IKP Cologne plunger [2], with the aim to measure the reduced transition probabilities for the \(4^+\rightarrow 2^+\) and \(2^+\rightarrow 0^+\) yrast transitions in \(^{94}\text{Ru}\) and \(^{92}\text{Mo}\) nuclei.

The multi-nucleon transfer (MNT) reaction mechanism has been unconventionally [3] used to populate the proton rich nuclei of interest. Contrary to fusion evaporation, MNT reactions allow, to populate directly medium to low angular momentum states, even in presence of isomers, thus, allowing the direct determination of the lifetimes.

In this experiment, a \(^{92}\text{Mo}\) beam with an energy of 716.9 MeV impinged in the stretched \(^{92}\text{Mo}\) target of the Plunger, while a \(^{24}\text{Mg}\) foil was used to degrade the energy of the reaction products. The reaction products of interest were identified with the magnetic spectrometer VAMOS++ [4], while the gamma-ray in coincidence were measured using AGATA [5].

Preliminary results on the obtained lifetimes and reduced transition probabilities for the \(4^+\rightarrow 2^+\) and \(2^+\rightarrow 0^+\) yrast transitions in \(^{94}\text{Ru}\) and \(^{92}\text{Mo}\) will be shown. In this contribution these results will be interpreted on the basis of shell model predictions, allowing also for the comparison of the nuclear structure trends between the valence mirror symmetry partners \(^{56-78}\text{Ni}\) \(Z=28\) isotopes and \(^{78}\text{Ni}\)-\(^{100}\text{Sn}\) \(N=50\) isotonic chain.

References:
Gamma-spectroscopy of Neutron-rich $^{79}$Cu Through Proton Knockout

OLIVIER, Louis 1; DR. FRANCHOO, Serge 1; DR. DOORNENBAL, Pieter 2; DR. OBERTELLI, Alexandre 3; THE SEASTAR COLLABORATION, SHELL EVOLUTION AND SEARCH FOR TWO-PLUS ENERGIES AT RIKEN 4

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Nuclear shell structure is evolving when going into more and more exotic regions. As a consequence, the conventional magic numbers can be different far from stability. Over the last years, the RIB factory at RIKEN has become available, providing primary beam of uranium with intensities that are now sufficient for gamma spectroscopy of neutron-rich copper isotopes next to $^{78}$Ni ($Z=28, N=50$).

We shall present the results of the in-beam spectroscopy of $^{79}$Cu ($N=50$), produced through the $^{80}$Zn($p$,2$p$)$^{79}$Cu knockout reaction at RIKEN. A $^{238}$U beam, with an energy of 345 MeV/nucleon, was sent on a $^9$Be target, creating a cocktail of radioactive isotopes. These isotopes went through the BigRIPS spectrometer, for identification and selection, and reached MINOS [1], a liquid-hydrogen target surrounded by a TPC used for proton tracking, where the knock-out reactions took place. The isotopes produced went through the ZeroDegree spectrometer for identification. The DALI2 scintillator array was surrounding MINOS for $\gamma$-ray detection. $\gamma\gamma$ coincidences permitted to build the first level scheme of $^{79}$Cu, with levels up to 4.6 MeV, and the results were compared to Monte-Carlo shell-model calculations [2]. We show that the $^{79}$Cu nucleus can be described in terms of a valence proton outside a $^{78}$Ni core, implying the magic character of the latter.


Transition Strengths in $^{22,23}$Mg as Tests of ab Initio Theory

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Recent theoretical developments in ab initio nuclear theory techniques make calculations of the properties of sd-shell nuclei possible without a reliance on phenomenology. In particular, in-medium similarity renormalization group (IM-SRG) and coupled-cluster theory have demonstrated promising results in describing the collective properties of nuclei, for example in self-conjugate $^{20}$Ne and $^{24}$Mg [1, 2, 3]. In principle, such techniques might allow for the elimination of phenomenological effective charges, accounting for physics lost in model truncations by correctly evolving the necessary operators.

Two Coulomb-excitation measurements were performed with the TIGRESS setup at the TRIUMF ISAC-II facility with the goal of providing precise E2 transition strengths in $^{22,23}$Mg to allow for more detailed scrutiny of results from modern, ab initio methodologies. Furthermore, in a previous measurement an apparent deviation in the ratio of isoscalar and isovector contributions to the E2 transition strength was observed in $^{21}$Na [4]. The results of the present measurement will be used to determine whether this deviation extends to neighbouring nuclides.

The results of the two measurements will be presented and compared with modern nuclear theory, both ab initio and phenomenological, including a first measurement of the sign of the diagonal matrix element of the first-excited 2$^+$ state in $^{22}$Mg through the reorientation effect. Results will be presented in the context of other Tz = −1, −1/2 isotopes, providing for a systematic evaluation of transition strengths within the sd-shell.

Breakout B2

Shape Isomerism in $^{66}$Ni

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The phenomenon of shape isomerism is related to the existence, in the nuclear potential energy surface (PES), of a secondary minimum associated with large deformation and separated from the primary minimum (ground state) by a high barrier. Shape isomers at spin zero have clearly been observed, so far, only in actinide nuclei. The existence of shape isomers in lighter systems has been a matter of debate for a long time: a rather restricted number of candidates was suggested by various mean-field theoretical approaches [1,2,3] and $^{66}$Ni turned out to be the lightest nucleus for which all models indicate the existence of a pronounced secondary PES minimum.

In $^{66}$Ni, among the six lowest excited states three have spin-parity assignment 0+. Monte Carlo Shell Model Calculations [4] which correctly predict the existence of all these three excited 0+ states, show that the 0+4 excitation should exhibit well-deformed prolate shape and be separated by a substantial barrier from the spherical main minimum. Indeed, the calculated B(E2) probability from 0+4 into the spherical 2+ is found to be significantly hindered pointing to the 0+4 state as a candidate for shape isomer.

To check this prediction, we performed a measurement of the lifetimes of 0+ excitations in $^{66}$Ni at the Bucharest Tandem Laboratory. By employing the two-neutron transfer reaction $^{64}$Ni($^{18}$O,$^{16}$O)$^{66}$Ni, at sub-barrier energy of 39 MeV, all three lowest-excited 0+ states in $^{66}$Ni were populated and their gamma-decay was observed by employing gamma-coincidence technique with the ROSPHERE HPGe array. The population pattern of the 0+ states clearly indicated that 0+4 corresponds to the prolate deformed 0+ excitation predicted by theory. The 0+ states lifetimes were measured with a plunger device and, in particular, for the 0+4 to 2+1 decay the B(E2) values of 0.2 W.u. was found. The measured hindrance of E2 decay from the prolate 0+4 to the spherical 2+1 state is in line with the results of MCSM calculations, although the experimental magnitude is smaller. This result makes $^{66}$Ni a unique nuclear system, apart from $^{236}$U and $^{238}$U, in which a retarded gamma-transition from a 0+ deformed state to a spherical configuration is observed, pointing to a shape isomer-like behaviour.


Breakout B2

E0 Transitions and Shape Coexistence in $^{54,56,58}$Fe

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Doubly magic nuclei and their nearest neighbours serve as an ideal testing ground for the nuclear shell model, and consequently enable us to define effective nuclear interactions. Collective states in nuclei near $^{56}$Ni can be attributed to multiparticle-multihole excitations from the 1f 7/2 to the 2p 3/2, 1f 5/2 and 2p 1/2 orbits across the N, Z=28 shell gap. Properties of excited 0+ states as well as E0 and E2 transition strengths are sensitive probes of the underlying nuclear structure.

A systematic study of the stable N=28-32, even-even iron isotopes was performed and E0 transitions between the lowest excited 0+ states and the ground states were measured. Data were obtained in an experimental campaign at the ANU Heavy Ion Accelerator Facility. Excited states of $^{54,56,58}$Fe were populated using (p,p') reaction at beam energies of 6.9 MeV ($^{54}$Fe), 6.7 MeV ($^{56}$Fe) and 7.0 MeV ($^{58}$Fe). Internal conversion electron and electron-positron pair spectra were measured using the superconducting electron spectrometer “Super-e”, and singles γ-rays were measured with a HPGe detector. In addition, the investigation is supplemented with information on angular distributions, angular correlations, and γ-γ coincidences, measured with the CAESAR detector array under the same experimental conditions. In order to deduce E0 matrix elements, the experimental data was evaluated using the available lifetime information from Doppler-shift attenuation measurements following inelastic neutron scattering, carried out at the University of Kentucky. Results and interpretation of the systematic study, as well as a more detailed description of the experiment and procedure will be presented in this talk.
**Breakout B2**

**The Nature of 0+ States in Deformed Nuclei**

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The existence and characterization of multi-phonon vibrational modes in deformed nuclei remains an open question in nuclear structure. The question revolves around the possible degrees of freedom in deformed nuclei [1-4]. Rotational motion is an expected feature of deformed nuclei, the open challenge is whether the granularity of nuclei allows single or multiple quanta of vibrational oscillations or excitations superimposed on the equilibrium deformed shape of the nucleus.

The lowest lying such shape effecting oscillations or vibrations would be quadrupole in nature, resulting in two types of vibrations: beta (K=0+) with no projection on the symmetry axis and gamma with a projection of K=2+. Vibrational spectra can, in principle, be constructed from one or more quanta of these states resulting in two-phonon \( \beta\beta \) (K=0+), \( \beta\gamma \) (K=2+), and \( \gamma\gamma \) (K=0+ and 4+) types of vibrational excitations. Single phonon gamma vibrational bands and low-lying K=0+ bands have been known for some time and they are abundant in various regions of deformation, including the rare-earth region of nuclei, albeit without systematic knowledge of level lifetimes. The gamma vibration seems to be well characterized as the first excited K=2+ band and exhibits a systematic behavior across the region of deformed nuclei with typical B(E2; 2+ \rightarrow 0+g.s.) values of a few Weisskopf units (W.u.). The energies of the first excited K=0+ bands and their B(E2) values show a different picture. The energies and associated B(E2) values of the first excited K = 0+ bands vary greatly throughout the deformed region. There are several examples of two-phonon quadrupole vibrational excitations in a number of nuclei exhibiting various degrees of the full collective transition strength with wide ranges in energy anharmonicities.

Yet, the question regarding the viability of the K= 0+ excitations as the beta-vibration in deformed nuclei remains open to discussion and debate. I would like to present some of our recent lifetime measurements across isotopic chains of the Gd, Dy, and Er isotopes to contribute to the discussion.

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**Plenary Wednesday**

**Electromagnetic Response in Nuclei: From Few- to Many-body Systems**

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The electromagnetic response of nuclei is a fundamental quantity to calculate, since due to its perturbative nature a clean comparison with experimental data can be performed. First principles computations are key to bridge nuclear physics with the underlying QCD regime [1]. Nowadays this valuable information is not only accessible for the lightest nuclei, but novel theoretical approaches are being developed to tackle nuclei with a larger number of nucleons.

Combining the Lorentz integral transform with the coupled-cluster method recently allowed us to perform ab initio calculations of response functions and related sum rules for light and medium-mass nuclei [2,3]. I will present recent highlights on neutron skins and polarizabilities and discussed them in the context of recent and future experiments [4,5].

**References:**

Plenary Wednesday

Nuclear Forces for ab Initio Nuclear Theory

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Predictive power requires the ability to quantify theoretical uncertainties. While it is true that theoretical error estimates are difficult to obtain, the pursuit thereof plays a pivotal role in science. Reliable theoretical errors can help to determine to what extent a disagreement between experiment and theory hints at new physics, and they can provide input to identify the most relevant new experiments. In this talk I will show that nuclear theory is at a stage where such questions can be addressed. Chiral effective field theory can be used to systematically bridge the gap from low-energy quantum chromodynamics to nucleons and pions as effective nuclear-physics degrees of freedom. Following this avenue we have made the quantification of theoretical uncertainties possible through the incorporation of state-of-the-art statistical and computational tools. In particular, we employ two different approaches to determine the coupling constants of chiral nuclear interactions: (1) The simultaneous optimization of nucleon-nucleon, pion-nucleon and few-nucleon data, and (2) In-medium optimization for which binding energies and radii of selected isotopes of carbon and oxygen are also used as input data. I will present results from both of these different approaches that together provide important steps towards our understanding of nuclear forces.

Plenary Wednesday

Where is the Neutron Drip-line for Oxygen?

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The presence of neutron and proton shell closures in the nucleus $^{28}$O, together with strong continuum coupling effects, make neutron-rich oxygen isotopes a unique laboratory for testing nuclear models. In this work, we investigate neutron-rich oxygen isotopes using the Gamow Shell Model and the Density Matrix Renormalization Group method with an effective finite-range two-body interaction optimized to the bound states and resonances of $^{23-26}$O assuming a core of $^{22}$O. Our results suggest the existence of narrow excited states in $^{25}$O and $^{27}$O decaying by neutron and gamma emission, and a near-threshold ground-state for $^{28}$O.

Plenary Wednesday

Ab Initio Studies of Nucleonic Matter

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Nucleonic matter has important implications on many branches of nuclear science: from the bulk properties of exotic nuclei to the equation of state of neutron star matter. After we have extended the self-consistent Green’s function (SCGF) theory to account for three-nucleon forces, it is now possible to make reliable predictions of nucleonic matter at both zero and finite temperatures and with full chiral interactions, a task that was not possible until a few years ago. The talk will present the SCGF approach as a very convenient way to investigate microscopic and thermodynamical properties of nucleonic matter. Among recent results, the prediction of the liquid-gas phase transition critical temperature in symmetric matter appears to be in reasonable agreement with experimental outcomes. Also studies of both saturation properties and finite temperature behaviors in infinite matter are pointing towards the necessity to refine the fitting procedure of low-energy constants. Moreover, I will show how first-principle tests of thermal approximations used in equations of state to study stellar environments questions the validity of such simulations.
Plenary Wednesday

The Difference a Few Neutrons Makes in the Fusion of Light Nuclei: Structure and Dynamics

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Fusion of neutron-rich light nuclei at near barrier energies involves the interplay of both structure and dynamics. Examination of fusion for an isotopic chain of nuclei provides a means to access the low density tail of the neutron density distribution and the polarizability of nuclear matter. Development of a new technique that allows measurement of the fusion cross-section at near barrier energies will be presented. The direct measurement of fusion residues with this technique is used to extract the fusion cross-section. The measured fusion excitation functions for ¹⁸,¹⁹O + ¹²C and ³⁹,⁴⁷K + ²⁸Si will be shown and the observed fusion enhancement will be compared with theoretical model predictions.

Plenary Wednesday

How Does Breakup of Light Weakly-bound Projectiles Affect Fusion?

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Fusion reactions provide the means to discover new elements, produce new exotic isotopes, investigate nuclear structure, and study many-body quantum dynamics. The fusion of light, weakly-bound projectiles (e.g., ⁶,⁷Li, ⁹Be) with heavy targets at above-barrier energies is found to be suppressed by 25-35% compared to both model expectations, and to fusion of strongly-bound projectiles [1]. This presents a major challenge to our understanding of fusion, particularly for measurements with nuclei far from stability.

Due to their low breakup thresholds, direct breakup of these nuclei into their intrinsic clusters (⁶Li→αd, ⁷Li→αt, ⁹Be→ααn) may prevent fusion – after breakup, capture of the complete charge of the projectile is hindered. Although these direct breakup modes are present, many unbound states are also accessible via nucleon transfer [2]. For example, ⁷Li can disintegrate through proton pickup, forming unbound ⁸Be. This mode becomes dominant as the target mass decreases, with direct breakup negligible for A<60 [3].

To infer the influence of breakup on fusion we need to understand both the mechanisms causing breakup and their timescales. Narrow resonances such as the ⁸Be 0⁺ (τ≈10⁻¹⁶ s) survive much longer than the collision time (10⁻²¹ s), and will arrive at the fusion barrier intact. Thus they are not expected to contribute to fusion suppression. Only if breakup occurs on the timescale of the collision (e.g. via the short-lived ⁸Be ²⁺ state) can fusion be suppressed.

Here we discuss recent measurements of sub-barrier breakup and their interpretation in terms of a classical dynamical model [4]. In the absence of a quantum model for transfer triggered breakup, classical trajectory models were developed, guided by experimental insights, to understand breakup and incomplete fusion in near-barrier collisions. Comparison with experimental measurements have shown how the correlations of the breakup fragments are altered by their proximity to the target nucleus at breakup [5] providing a probe of breakup timescales. These results suggest that the detailed structure of the intermediate states populated is crucial in determining the influence of breakup on fusion.

References:
Plenary Wednesday

Progress in Fission Investigated in Complete Kinematic Measurements

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The observation of asymmetric fission in 1948 was one of the main discoveries promoting the nuclear shell model. However, more than 75 years after its discovery fission still represents a challenge for nuclear physicists. In particular, the stabilization of the heavy fission fragment around A~140 initially explained in terms of the double shell closure around Z=50 and N=82 or N~88 was questioned by K.H. Schmidt and collaborators ten years ago. More recently, asymmetric fission partitions around 180Hg were observed by A. Andreyev and collaborators and interpreted by P. Moller without any shell effects.

Concerning the dynamics of fission the situation is not better. Pre- and post-scission particle emission and fission probabilities indicate that simple statistical approaches are not valid and models describing the dynamics of the process are required. Because of the complexity of time-dependent microscopic approaches, models based on transport equations (e.g. Fokker-Planck or Langevin) including dissipative and stochastic terms where the main ingredients are the potential landscape and the friction and inertia tensors are used. The friction or viscosity parameter is particularly interesting since it quantifies the magnitude of the coupling between collective and intrinsic degrees of freedom in fission.

The complete isotopic and kinematic identification of both fission fragments recently achieved using Coulomb induced fission in inverse kinematics should represent a real breakthrough in the investigation of fission providing answers to many of the open questions. In the near future this experimental progress could even improve taking advantage of quasi-free nucleon scattering inducing fission, e.g. (p,2pf).

Plenary Wednesday

Microscopic Theory of Nuclear Fission

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Since its discovery in the late nineteen thirties, nuclear fission has remained one of the most complex and elusive problems in physics and gaps in our understanding of this phenomena can impact progress in other areas. For example, in basic science accurate knowledge of spontaneous fission half-lives is key to predicting the stability of superheavy elements, and fission fragment charge and mass distributions are also important ingredients in simulations of the formation of elements in nuclear capture processes (fission recycling). In applications of nuclear science for energy production, fuel cycle optimization is also strongly dependent on the characteristics of the fission process in actinides. In all these examples, measurements are either difficult, for technological, financial or safety reasons, or simply impossible. Therefore, most information comes from theoretical predictions. These predictions are often based on powerful semi-phenomenological models that have been developed several decades ago and have been finely tuned on existing data, which limits their predictive power. In an ideal world, a predictive theory of fission should instead be based solely on quantum many-body methods and our best knowledge of nuclear forces. Today, there is a consensus that the nuclear energy density functional theory (DFT) is currently the best framework to achieve a microscopic description of fission. Unfortunately, the proper implementation of nuclear DFT comes at a tremendous computational cost, which explains why progress had been relatively slow in the past. The recent development of leadership computing facilities in the USA, Europe and Asia has, however, introduced a paradigm shift: Calculations that were simply unfeasible only 5 or 10 years ago can now be completed in just a few hours. Such a massive increase in computing power has opened entirely new perspectives and triggered a spectacular renaissance of fission studies. After a historical introduction to fission theory and models, I will give an overview of the DFT approach to nuclear fission and highlight a few selected results.
Evening Lecture Wednesday

Don’t be Such a Scientist: The Intersection of Science, Communication and Policy

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For most of our professional lives, we perform fundamental research with a goal towards solving problems that advance scientific knowledge. Such a career requires significant investment in education, skill in analytical thinking and problem solving, and usually some sort of sustained federal funding of instrumentation and personnel. Although the costs associated with basic research are small compared to other federal expenditures, in the current funding era we are increasingly asked to justify the taxpayer investment in scientific research. Simultaneously, we wish to continue to attract the best students into our field. Both the persuasion of people to support a pro-science policy and the attraction of new people into a STEM career require better communication skills than most of us have ever developed. In Randy Olsen’s book: “Don’t be Such a Scientist”, he argues that we have done such a poor job communicating science that we are lucky it continues in the US at all!

The evolution of one particular scientific career from basic nuclear science into one with an applied environmental science direction using nuclear science techniques will be presented. This includes using ion beam analysis to study lake sediments, and to trace flame retardants from consumer products into our environment. Recent studies focus on an emerging class of chemicals of concern (Per- and Polyfluorinated Alkyl Substances) that are ubiquitous in textiles, food packaging, personal care products and industrial uses. But the most significant of these findings required improved communication skills in order to achieve any significant effect on science policy. Therefore, it could be argued that more of us should develop the type of communication skills necessary to alter the science policy landscape in the US.
Plenary Thursday

Nuclear Structure Studies by Measurements of Nuclear Spins, Moments and Charge Radii Via Collinear Laser Spectroscopy at ISOLDE

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High-resolution laser spectroscopy at ISOLDE gives access to properties of nuclear ground states and long-lived (> 5ms) isomeric states of radioactive nuclei far from stability, such as nuclear spins, nuclear magnetic and quadruple moments and charge radii [1]. These fundamental properties of exotic nuclei provide important information for the investigation of the nuclear structure in different regions of nuclear chart. Currently, two complementary collinear laser spectroscopy set-ups are available at ISOLDE: one for optically detected Collinear Laser Spectroscopy (COLLAPS) [2] and one for Collinear Resonant Ionization Spectroscopy (CRIS) [3].

By combining these two techniques, the nuclear structure in several key regions of the nuclear chart is been studied, from the very neutron-deficient to the very neutron-rich side of the nuclear landscape. Recent results from studies in the Ca and Ni regions will be presented and an outlook to future opportunities will be presented.

References:

Plenary Thursday

Manifestation of Three-nucleon Spin-orbit Interaction in Nuclear Charge Radii

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The nuclear charge radii have supplied high-precision and model-independent data on nuclear structure. In particular, thanks to the collaboration of atomic physics, difference of the charge radii among isotopes, i.e. isotope shifts (field shifts, to be more precise), have been measured with striking precision. The isotope shifts have been known to be a good indicator for variation of nuclear structure along an isotopic chain. They may also provide information of the nucleonic interaction. The isotope shifts in the Pb nuclei was suggested to be relevant to the isospin content of the nucleonic LS interaction two decades ago. However, fictitious degeneracy or level inversion had to be introduced to reproduce the observed kink in the isotope shifts of the Pb nuclei.

Via a self-consistent mean-field (SCMF) study, I point out that the three-nucleon (3N) interaction, which has been indicated by the chiral effective field theory (EFT) and pointed out to narrow the gap between the theoretical description and experiments of the ls splitting, may also solve the problem of the isotope shifts. The kink in Pb is described fairly well with a reasonable single-particle-level difference between the relevant orbitals. It is found that the close charge radii between $^{40}$Ca and $^{48}$Ca, which is another long-standing problem, are well reproduced as well. As the SCMF calculations clarify physics mechanism how the 3N LS interaction influences the nuclear charge radii, these data can be regarded as a manifestation for the 3N LS interaction. It is suggested that kinks as observed in Pb can be universal at the neutron magicity in the isotopes with magic proton numbers. As an example, a kink is predicted in the isotope shifts of Sn at N=82, which will be a touchstone of this picture linking the nuclear radii and the 3N LS interaction.
Plenary Thursday

The Use of Storage Rings in the Study of Reactions at Low Momentum Transfers

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Several nuclear reactions are best investigated when the momentum transfer to the nucleus is small. Among these are the IsoScalar Giant Monopole Resonance (ISGMR) which helps determine one of the parameters of the equation of state, namely the incompressibility of nuclear matter, and proton elastic scattering from nuclei which is sensitive to parameters of nuclear density such as the matter root-mean-square radius. These have been extensively studied in the past using stable beams. However, with the advent of radioactive ion facilities around the world, it is desirable to study these reactions with unstable nuclei. The reactions, however, have to take place in inverse kinematics in which the radioactive ions impinge on a light target (hydrogen or helium). Simple kinematics calculations show that the outgoing recoil particles possess extremely low energies (down to few hundred keVs). External targets are, therefore, not suitable for these reactions. There are two alternative methods to deal with this challenge: either do the experiments in storage rings with gas jet targets or any other thin targets, or perform the measurements with an active target which also acts as a detector. In both cases, the energy threshold will be much lower than a fixed target of a reasonable thickness.

We have performed measurements with the radioactive 56Ni using both methods. In the ring measurements, proton elastic scattering was the main goal for this nucleus while feasibility studies were done with 58Ni and a helium target to investigate ISGMR. In this presentation, the experimental method used in the storage ring will be discussed along with some results, and a comparison will be made with the results of the active target measurements.

Plenary Thursday

Beta-delayed Neutron Spectroscopy with VANDLE, Evidence for Gamow-Teller Decay of 78Ni Core

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The beta-delayed neutron emission of neutron-rich isotopes near 78Ni and 132Sn regions were studied using the neutron time-of-flight technique with Versatile Array of Neutron Detectors at Low Energies (VANDLE). We have measured neutron energy spectra, which showed emission from states at excitation energies high above neutron separation energy. This effect was previously not observed in the beta-decay of mid-mass nuclei. For the example cases of 83,84Ge, large decay strength deduced from the observed intense neutron emission is a signature of Gamow-Teller transformation and was interpreted as evidence for allowed beta-decay to core-excited states of 78Ni. To describe the observed features of this decay, we have developed shell model calculations in the proton fpg9/2, and neutrons extended fpg9/2+d5/2 valence space using realistic interactions. Enhanced and concentrated beta-decay strength for neutron-unbound states may be common for very neutron-rich nuclei and would lead to intense beta-delayed high-energy neutrons or multi-neutron emission probabilities that in turn will affect astrophysical nucleosynthesis models.
Plenary Thursday

Shape Coexistence in Neutron-rich Strontium Isotopes at N=60

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Neutron-rich A~100 nuclei are among the best examples of interplay of microscopic and macroscopic effects in nuclear matter. A dramatic onset of quadrupole deformation is observed in the neutron-rich Zr and Sr isotopes at N=60, making this region an active area of experimental and theoretical studies. This rapid shape transition is accompanied by the appearance of low-lying 0^+ states.

Low-energy Coulomb excitation experiments were to study properties of coexisting structures in 96,98Sr (N=58,60) using post-accelerated exotic Sr beams from REX-ISOLDE. The experiments were carried out in the particle-gamma coincidence mode using the MINIBALL HPGe array coupled to an annular Double Sided Silicon Detector. Reduced transition probabilities and spectroscopic quadrupole moments were extracted from the measured differential Coulomb excitation cross sections. The results support the scenario of shape transition at N=60 giving rise to coexistence of two very different configurations in 96,98Sr. In 96Sr, the spectroscopic quadrupole moment of the first 2^+ state was found to be small and negative, corresponding to a weak prolate deformation. In 98Sr, the large and negative spectroscopic quadrupole moments in the ground state band prove its well-deformed prolate character, while the value close to zero obtained for the 2^+_2 state confirms that a spherical configuration coexists with the deformed configuration of the ground state. The comparison of the B(E2) values and the spectroscopic quadrupole moments between the 2^+_1 state in 96Sr and the 2^+_2 state in 98Sr underlines their similarity and further supports the shape inversion when crossing the N=60 line. Furthermore, a very small mixing between the coexisting structures was determined from measured intra-band transition probabilities in 98Sr. This effect has been attributed to the rapidity of the shape change at N=60; a larger mixing would give rise to a more gradual transition from spherical to deformed ground state in Sr isotopes, like what is observed in other areas of shape coexistence, for example neutron-deficient Kr and Hg isotopes.

The experimental results, together with a detailed comparison with new beyond-mean-field calculations, will be presented. The present work will be also highlighted in a larger framework of the shape change in the mass region.

Plenary Thursday

Recent Developments in Shape Coexistence Studies

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The information on collective properties of nuclei far from stability has dramatically improved in recent years due to the availability of radioactive ion beams used, e.g., for Coulomb excitation studies both below the Coulomb barrier and at relativistic energies. These studies are complemented by spectroscopic studies and lifetime measurements applied to other reaction mechanisms suitable for producing exotic nuclei.

Over the last few years we have carried out a research program using these complementary techniques, and applied them to several mass regions, where shape coexistence and a sudden evolution of nuclear shapes are expected. In this presentation recent results for two such mass regions will be presented, the A~70 nuclei at and beyond the N=Z line and neutron-rich nuclei in the A~100 region. In the first case the closeness and influence of the proton drip line on the shape properties is being explored, while in the second case the evolution of nuclear shapes beyond the onset of strong deformation at N=60 (in particular in Sr and Zr isotopes) as well as the importance of the triaxial degree of freedom in the Mo and Ru isotopes at N~64-70 are of strong current interest.

In this presentation recent results will be presented that were obtained using several different facilities: On one hand, using stable beams from GANIL and the combination of the VAMOS and EXOGAM spectrometers, heavy-ion induced fission was used to obtain new lifetime results in several Zr, Mo, Ru and Pd isotopes. On the other hand radioactive neutron-rich beams from the CERN-ISOLDE and ANL-Caribu facilities were used to perform Coulomb excitation experiments yielding new electro-magnetic matrix elements in the same nuclei. Finally, the even more exotic proton-rich nuclei around A~70 were studied using relativistic Coulomb excitation of fragmentation beams from the RIBF facility at RIKEN.
Plenary Thursday

First Experiment in the $^{100}$Sn Region Using HIE-ISOLDE

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In this presentation results from the first experiment with the new post-accelerator HIE-ISOLDE at CERN will be given. HIE-ISOLDE expands the possibilities offered by its predecessor, REX-ISOLDE, by increasing the final energy of the radioactive beam (RIB) to 5 MeV/u and 10 MeV/u in two steps, using a set of new superconducting cavities. The first step, to 5 MeV/u, facilitates e.g. the use of heavier targets in the Coulomb excitation program that was started with REX-ISOLDE. In practice this means that the earlier measurements, that were largely restricted to excitation of the lowest lying states in the RIB, now can include states at higher energies, and simultaneously substantially increase the statistics for the states addressed in the REX-ISOLDE campaign. The first production run with HIE-ISOLDE was part of the program in the $^{100}$Sn region. In this case the use of the new post-accelerator means that the measurements of the transition probabilities from the ground state to the first excited $2^+$ state in the light even Sn isotopes, that earlier were statistics limited, now are observed with some two orders of magnitude higher statistics. In addition, multi-step excitation is observed providing further information on the yrast sequence in these isotopes. The new results will be discussed and put into the context of earlier measurements and theoretical interpretations.

Plenary Thursday

Properties of Mg and S Isotopes in a Beyond Mean Field Theory.

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Traditionally effective interactions like Skyrme, Gogny or relativistic interactions have been used in basic mean field approaches to describe with great success bulk properties of ground states of nuclei, such as masses, quadrupole moments, radii, etc. However, recent developments in beyond mean field calculations, with particle number and angular momentum projection in conjunction with the Generator Coordinate Method (with the deformations $\beta \gamma$, pairing gaps ($\Delta Z, \Delta N$) and angular frequency as generator coordinates) have shown that the Gogny force [1,2] is also able to provide high quality nuclear spectroscopy. This approach has recently been extended to odd-even nuclei [3] allowing thereby to perform isotopic (isotonic) studies of nuclear properties. The strong point of this approach is the ability to simultaneously provide a good description of bulk properties, like binding energies and multipole moments, as well as an accurate and detailed account of excitation energies and transition probabilities.

As a validation of the theory in this talk we present a study of the Magnesium isotopic chain. We obtain an outstanding description of the ground-state properties, in particular binding energies, odd-even mass differences, mass radii and electromagnetic moments among others. At the same time a comprehensive study of the spectroscopic properties of $^{25}$Mg is discussed. These studies, together with the spectrum and the transition probabilities of the nuclei $^{42}$Si and $^{44}$S, show that these calculations provide an accuracy comparable with state-of-the-art shell model calculations with tuned interactions. The advantages of the present approach as compared to the shell-model one are the added value of the intrinsic system interpretation and that the interaction, the Gogny force, is well known for its predictive power and good performance for bulk properties all over the chart of nuclides.

References:
Breakout C1

High-resolution Laser Ionisation Spectroscopy of Heavy Elements in Supersonic Gas Jet Expansion

Dr. FERRER, Rafael 1; Prof. HUYSE, Mark 2; Prof. VAN DUPPEN, Pier 2; Mr. Vanden BERGH, Paul 2; Mr. GRANADOS, Camilo 2; Dr. KUDRYAVTSEV, Yuri 3; Mr. SELS, Simon 2; Mrs. ZADVORNAYA, Alexandra 2; Dr. LAATIAOUI, Mustapha 4; Mr. VERLINDE, Matthias 2; Mrs. VERSTRAELEN, Elise 2

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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 shape, size, spin and electromagnetic multipole moments of these nuclei. In such measurements, however, it is difficult to combine a high efficiency with a high spectral resolution. Recently, we have demonstrated the on-line application of atomic laser ionization spectroscopy in a supersonic gas jet, a technique suited for high-precision studies of the ground- and isomeric-state properties of nuclei located at the extremes of stability [1]. A significant improvement in the spectral resolution by more than one order of magnitude was achieved in these experiments without loss in efficiency.

Spatial constraints and limitations of the pumping system in the present setup prevented a high quality jet formation and, as a consequence, an optimal spatial and temporal laser-atom overlap. Offline characterization studies at the newly commissioned In-Gas Laser Ionization and Spectroscopy (IGLIS) laboratory at KU Leuven [2] are being carried to overcome these limitations in future experiments when dedicated IGLIS setups are in operation at new generation radioactive beam facilities [3]. These studies also include the characterization of the flow dynamics and the formation of supersonic jets produced by de Laval nozzles with different Mach numbers using the Planar Laser Induced Fluorescence technique on copper isotopes, the test of a new gas-cell design with better transport and extraction characteristics and the characterization of a high-power, high-repetition rate laser system. Extrapolation of the online results on the actinium isotopes show that the performance of the technique under optimum conditions can reach a final spectral resolution of 100 MHz (FWHM) and an overall efficiency of 10% when applied in the actinide region.

In this presentation we will briefly summarize the on-line results and mainly will focus on the characterization studies and future prospects of the in-gas-jet resonance ionization technique applied on very-heavy elements.

References:
Breakout C1

Recent Technical Developments and New Scientific Endeavors at IGISOL

Prof. MOORE, Iain 1; Ms. CANETE, Laetitia 1; Mr. POHJALAINEN, Ilkka 1; Dr. REPONEN, Mikael 1; Dr. RINTA-ANTILA, Sami 1; Dr. VOSS, Annika 1; Dr. ERONEN, Tommi 1; Ms. GELDHOF, Sarina 1; Prof. JOKINEN, Ari 1; Dr. KANKAINEN, Anu 1; Dr. NESTERENKO, Dmitrii 1; Dr. PENTTILÄ, Heikki 1

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Since the successful commissioning of the IGISOL-4 facility, Jyväskylä, throughout 2012-2014 [1], we have moved towards full operation. The gradual evolution of the ion guide method for a universal production of both volatile and non-volatile elements has been driven by the pursuit of physics research on both sides of the valley of beta stability. The ongoing development of new ion (and atom) manipulation techniques as well as new production methods at IGISOL-4 has been driven by the needs of the evolving scientific program.

This contribution will provide an overview of the current status of developments as well as highlighting new themes of research. In collaboration with Uppsala University we have been simulating the fission process to understand the stopping and extraction efficiency of the ion guide used for proton-induced fission [2]. Importantly, this also supports and guides our experimental progress towards neutron-induced fission. The latter has seen the characterization of neutron energies and intensities at different angles using neutron activation and time-of-flight methods [3]. In December 2016 we successfully extracted stopped fission fragments products using neutron-induced fission for the first time.

In order to provide a variety of stable beams of elements required for laser spectroscopy as well as mass spectrometry, an off-line ion source which combines discharge-, surface ionization and (in the future) laser ablation, has been commissioned.

A core theme of the facility is the program of optical spectroscopy and laser developments. I will summarize the current status of our expansion of the solid state laser infrastructure for use in collinear laser spectroscopy. Exciting new programs include laser ionization of long-lived actinide isotopes coupled with high-resolution spectroscopy [4,5], as well as a new research theme in cold atom physics. This latter theme, led by University College London, has seen the installation of a new atom trap with the goal of achieving coherent gamma-ray emission via a Bose-Einstein Condensate of $^{135m}$Cs isomers.

References:

Recent Upgrades of the Penning-trap Mass Spectrometer SHIPTRAP for High-precision Mass Measurements

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Penning–trap mass spectrometry allows direct and reliable measurements of atomic masses with very high precision. This technique is especially suitable to investigate the nuclear structure evolution of radioactive nuclides through measurements of binding energies. The heaviest elements investigated to date in pioneering experiments with the SHIPTRAP setup at GSI, Darmstadt, have been nobelium and lawrencium [1,2]. The existence of such heavy nuclei is intimately connected to nuclear shell effects that stabilize them against spontaneous fission. The direct measurement of the masses of $^{252-255}$No and $^{255,256}$Lr has allowed mapping the strength of the deformed subshell closure at $N=152$.

In order to extend such studies to heavier and more exotic nuclides, the efficiency, precision and sensitivity of the SHIPTRAP setup is being further increased [3]. In particular, a cryogenic buffer gas-stopping cell [4] has been recently commissioned and the whole SHIPTRAP setup has been relocated on a 3-degree beam line at the SHIP (Separator for Heavy Ion reaction Products) recoil separator, in preparation for future online campaigns aiming at direct mass measurements of elements beyond Lr.

To this end, the novel Phase-Imaging Ion-Cyclotron-Resonance technique (PI-ICR) [5], recently developed at SHIPTRAP, will be applied for the first time to the region of the heaviest elements. This new method allows mass measurements with only a few ion counts, i.e. at the lowest production yields. In addition, it reaches an accuracy level of $10^{-9}$, even for short-lived nuclides ($T_{1/2}$ ≤ 1s).

Such high precision is required in the context of neutrino physics, another field of SHIPTRAP activities, for instance in Q_{β/EC} measurements [6]. Q-values with uncertainties of few eV are demanded in experiments that aim at the determination of the neutrino mass (hierarchy) or the search for neutrinoless double-β decays. This contribution will present an overview of the recent results of the measurements related to the neutrino physics as well as the present status of the SHIPTRAP setup.

References:
New ISOLDE Setup for Laser Polarization and for Studies Using Spin-polarized Nuclei

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Spin-polarized beams of radioactive nuclei can be of interest for studies in different fields, such as nuclear structure, fundamental interactions, or material science and life sciences. This is the motivation behind a recent initiative to build a permanent ISOLDE beamline, called VITO, devoted to various studies with polarized and non-polarized beams, as described in Ref. [1]. Within this initiative, we have recently developed the experimental setup which allows to polarize with lasers the ions and atoms of interest, detect their polarization via beta-decay asymmetry and in addition, use these beams for various studies, including beta-detected NMR and fundamental interaction investigations.

The experimental setup for spin-polarization with lasers and for beta-asymmetry studies was designed at the beginning of 2016. It was installed at ISOLDE in the summer of 2016 and successfully commissioned with spin-polarized radioactive beam of 26,28Na in autumn 2016 [2]. The next stages of the project include a system to perform studies in liquid hosts as well as a setup for beta-gamma and decay spectroscopy on spin-polarized nuclei.

This contribution will briefly review the principles of laser spin polarization and beta-NMR spectroscopy, it will present in detail the newly installed experimental setup and the results of the commissioning beam time, and will close by the presentation of the planned experiments [1, 3].

References:
Breakout C1

Advancing Penning Trap Mass Spectrometry of Rare Isotopes at the LEBIT Facility

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The Low-Energy Beam and Ion Trap (LEBIT) facility [1] at the National Superconducting Cyclotron Laboratory (NSCL) remains the only facility that employs Penning trap mass spectrometry for high-precision mass measurements of rare isotopes produced via projectile fragmentation. This powerful combination of a fast, chemically insensitive rare isotope production method with a high-precision Penning trap mass spectrometer has yielded mass measurements of short-lived rare isotopes with precisions below 10 ppb across the chart of nuclides. The most recent LEBIT measurement campaigns have focused on fundamental interactions such as T=1/2 mirror decay Q-values (C-11 [2] and Na-21 [3]), and superallowed β decay Q values (O-14 [4]), and the nuclear mass surface near N=40 (Co-68,69). LEBIT has also recently been used to measure the Q-values of several neutrinoless β-decay candidates and highly forbidden decays, using ions produced offline with local ion sources.

In order to expand the experimental reach of Penning trap mass spectrometry to nuclides delivered at very low rates, the new Single Ion Penning Trap (SIPT) has been built. SIPT uses narrowband FT-ICR detection under cryogenic conditions to perform mass measurements of high-impact candidates, delivered at rates as low as one ion per day, with only a single detected ion. Used in concert with the existing LEBIT 9.4-T time-of-flight mass spectrometer, the 7-T SIPT system will ensure that the LEBIT mass measurement program at NSCL will make optimal use of the wide range of rare isotope beams provided by the future FRIB facility.

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References:
Breakout C1

BRIKEN Beta-delayed Neutron Detector Array at RIKEN*

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Beta-delayed neutron emission ($\beta n$) points to the structure of involved nuclei and helps to understand the competition of allowed and first forbidden $\beta$-transition during the decay process. The resulting $\beta 1n$ and $\beta xn$ branching ratios affect the nucleosynthesis pattern in the r-process [1].

BRIKEN array has been assembled by a multinational collaboration at the BigRIPS separator at RIKEN laboratory (Wako, Japan) to study the decay properties of the most neutron-rich nuclei produced through the fragmentation of high intensity $^{238}U$ beam. BRIKEN includes the world-largest array of $^3$He counters, highly segmented silicon detectors AIDA [2] and Ge clovers. $^3$He tubes and Ge signals are analyzed using Struck digital modules.

The efficiency of present hybrid BRIKEN configuration at BigRIPS, with 140 $^3$He tubes and 2 clovers, is over 60% over a wide $\beta n$ energy range up to few MeV [3]. Four accepted experiments aim in a large number of $\beta n$-emitters to be studied for the first time. The proposed studies cover the regions of nuclei from $^{76}Co$ to $^{167}Eu$.

In particular, it is intended to measure new beta-delayed neutron ($\beta n$) emission properties for nuclei near doubly-magic $^{78}Ni$. The first direct measurement of 20 $P_{1n}$ values for nuclei between $^{76}Co$ and $^{92}Se$ including that of the doubly-magic $^{78}Ni$ as well as the discovery of 14 $\beta 2n$ emitters between $^{80}Cu$ and $^{91}As$ and the determination of their $P_{2n}$ values is expected.

BRIKEN was partially commissioned in 2016 during parasitic studies with $^{238}U$ and $^{48}Ca$ fragments. The main experiments are likely to be performed in early May 2017.

Supported by the U.S. DOE Office of Science. Project partially supported and inspired by the IAEA Coordinated Research Project for a "Reference Database for beta-Delayed Neutron Emission."

References:
* presentation on behalf of BRIKEN Collaboration

Breakout C1

Recent Results From the Active Target Time Projection Chamber

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The Active Target Time Projection Chamber (AT-TPC) built at NSCL was recently commissioned using re-accelerated beams from the completed ReA3 linac. This detector is well suited to the energy domain covered by this accelerator, around the Coulomb barrier, using inverse kinematics reactions with radioactive nuclei. Its main asset is the enhanced luminosity gained from the active target concept that allows to use a thick target while retaining the good resolutions necessary for this type of scattering experiments. Another important aspect is the ability to measure excitation functions of reactions from a single beam energy. Data taken on the reactions $^4He+^4He$ at 2-3 MeV/u and $^{46}Ar+p$ at 4.6 MeV/u will be presented, as well as the methods and processes used in the analysis. The latter reaction was the first experiment performed with a re-accelerated radioactive beam at the NSCL. Its aim is to study the structure of $^{47}Ar$ via the measured properties of resonant analog states in $^4K$ populated via the $^{46}Ar+p$ elastic scattering reaction at Coulomb energies. Although widely used in direct kinematics with stable targets, this method hasn’t been so farapplied to radioactive beams in inverse kinematics for medium to heavy mass nuclei. Methods for track analysis and noise rejection will be shown. Future developments of the detector and its electronics to improve the quality of this type of data will also be presented.
Breakout C1

The ISOLDE Facility and the HIE-ISOLDE Project, Recent Results

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ISOLDE is the CERN facility dedicated to the production of radioactive ion beams for many different experiments in the fields of nuclear and atomic physics, materials science and life sciences. The ISOL method involves in this case the bombardment of a thick target with an intense proton beam, producing high yields of exotic nuclei with half-lives down to the millisecond range. By a clever combination of target and ion source units pure beams of over 1000 different nuclei of 74 elements have been produced and delivered to experiments where properties of the nuclei such as masses, radii, decay modes, structure and shapes are determined. This year ISOLDE celebrates its 50 anniversary of production of radioactive beams offering the largest variety of post-accelerated radioactive beams in the world.

The HIE ISOLDE upgrade (HIE stands for High Intensity and Energy), intends to improve the experimental capabilities at ISOLDE over a wide front. The main feature is to boost the energy of the beams, going in steps from previous 3 MeV/u via 5.5 MeV/u to finally 10 MeV/u, and to accommodate a roughly fourfold increase in intensity. In 2016 Physics with 5.5 MeV/u for A/q = 4.5 was available and six experiments were done with beams from 9Li to 142Xe and energies up to 6.8 MeV/u in the case of 9Li were achieved. In this contribution highlights from ISOLDE and from the HIE-ISOLDE project will be presented.

Breakout D1

Quantum Self-organization and Nuclear Shapes

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The nuclear deformation is driven by the quadrupole-quadrupole (QQ) component in the effective nucleon-nucleon (NN) interaction. Intuitively speaking, the actual nuclear shape is determined by the following mechanism: deformation = relevant driving force resistance. In the case of quadrupole deformation, the relevant driving force is the QQ force mentioned above, and a well-known example of the resistance is pairing interaction. There is another resistance power, that is, single-particle energies. If the single-particle orbits are separated too far, there is no sizable mixing among them, and hence no Jahn-Teller effect, namely, no deformation. Thus, single-particle energies, which can be viewed as the Nilsson levels at zero deformation, play crucial roles. Such single-particle energies have been considered to be close to constant within a nucleus. However, recent Monte Carlo Shell Model calculations on exotic Ni and Zr isotopes [1,2] showed that strongly-deformed bands are created and stabilized not only by strong effects of the QQ interaction but also by the change of single-particle energies of relevant orbits. For instance, in 98Zr, the relevant neutron single-particle orbits are spread over 5 MeV in its spherical ground state, whereas they become more degenerate within 2 MeV range in the first excited deformed 0+ state (Fig. 3 of [2]), due to massive proton excitations into g_{9/2} etc. We can regard this kind of phenomena as examples of the quantum self-organization, where atomic nucleus gains a certain shape (or collective mode in general) also by optimizing single-particle energies for this particular shape. This can be done if the NN interaction, particularly its monopole part, has rather strong orbital dependencies (e.g. tensor force) and the occupation numbers of relevant orbits can be reshuffled. This quantum self-organization can occur more frequently towards heavier nuclei with more orbits, exhibiting more beautiful rotational bands, for instance. The same mechanism can be applied to general many-body quantum systems with (i) mode-driving force and resistance controlling force, (ii) two Fermi liquids like protons and neutrons. In addition to shape coexistence and quantum shape phase transition, further developments will be discussed.

References:

Breakout D1

**Precision Mass Measurements of Nutron-rich Chromium Isotopes into the \( N=40 \) "Island of Inversion": From a New "ISOL" Beam to ab-initio Shell Model Calculations.**

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As first hinted at in the mid-seventies by pioneering on-line mass measurements of neutron-rich Na isotopes, the spherical shell, or sub-shell, gaps described within the shell model of the atomic nucleus are prone to rapid evolution with proton and neutron number. Far from being isolated, the region of shell erosion around \( N=20 \) is actually part of a larger “archipelago of islands of inversion”. One such island, around \( N=40 \), is thought to exhibit maximum quadrupole deformation for \(^{64}\text{Cr}\). However, the mass surface in the chromium chain, approaching \( N=40 \), remains too imprecisely known. Over the last thirty-years, on-line Penning-trap mass spectrometry associated with the “ISOL” production technique has proven to be a particularly successful tandem for the precise determination of the mass of exotic species. Although chromium was not considered to be a traditional thick-target “ISOL” element, successful laser-ionization developments [1] combined with highly sensitive mass spectrometry techniques enabled the mass measurements of \(^{52-63}\text{Cr}\), during two recent experimental campaigns at the ISOLDE facility, using the Penning-trap mass spectrometer ISOLTRAP[2]. The mass values obtained are of greatly refined precision thus shining new light on the development of ground-state collectivity towards \( N=40 \) in the chromium chain. Very recently, an ab-initio method, rooted in the IM-SRG framework, has been developed enabling the derivation of shell-model Hamiltonians from first principles thus extending the reach of ab-initio calculations to mid-shell nuclei [3]. A comparison of these state-of-the-art shell model calculations with our results will be presented.

References:
High-sensitivity and High-resolution Laser Spectroscopy of $^{76,77,78}\text{Cu}$ at CRIS

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The Collinear Resonance Ionization Spectroscopy experiment (CRIS) at ISOLDE combines the high sensitivity of resonance ionization spectroscopy with the high resolution offered by collinear laser spectroscopy. The first experiments at CRIS demonstrated the ability to reach exotic isotopes, normally out of reach for collinear laser spectroscopy methods based on photon detection, with an intermediate resolution [1]. Further developments have focused on improving the resolving power, to the point where it now matches the resolution of other collinear laser spectroscopy methods [2]. With this performance, the CRIS experiment is ideally suited to study the evolution of nuclear structure in regions far from stability.

Several ISOLDE experiments have been working towards the region around the doubly magic $^{78}\text{Ni}$. Previous laser spectroscopy work [3-7] clearly demonstrated the inversion of the $\pi f_{5/2}$ and the $\pi p_{3/2}$ orbitals between $^{73}\text{Cu}$ and $^{75}\text{Cu}$ as the $\nu g_{9/2}$ orbital is filled. This inversion is currently understood in terms of the tensor interaction between the neutrons and protons [8] which could potentially result in a quenching of the $Z=28$ shell gap towards $N=50$ [9].

This contribution will focus on the application of the high-resolution CRIS technique to the study of neutron-rich copper isotopes in the vicinity of $N=50$. The g-factors, quadrupole moments and charge radii of these neutron-rich copper isotopes will provide additional information to gauge the robustness of the magicity of the $Z=28$ shell in $^{78}\text{Ni}$. During the last campaign in April 2016, measurements have been performed on 15 Cu isotopes, including for the first time high resolution measurements of the very exotic isotopes $^{76,77,78}\text{Cu}$, where $^{78}\text{Cu}$ was produced at a rate of only 20 ions/s. These measurements provide information on the spin, magnetic moment, quadrupole moment and charge radius. The obtained data will be compared to large scale shell model calculations.

References:

Breakout D1
Weakly Bound and Unbound Light Nuclei From ab Initio Theory

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In recent years, significant progress has been made in ab initio nuclear structure and reaction calculations based on input from QCD employing Hamiltonians constructed within chiral effective field theory. One of the newly developed approaches is the No-Core Shell Model with Continuum (NCSMC) [1,2], capable of describing both bound and scattering states in light nuclei starting from chiral two- (NN) and three-nucleon (3N) interactions. We will present latest NCSMC calculations of weakly bound states and resonances of the exotic halo nucleus 11Be and discuss its strong E1 transitions and photo-dissociation [3]. We will also discuss its mirror 11N, an unbound 10C+p system, and highlight the role of chiral NN and 3N interactions in the description of the 10C(p,p) scattering measured recently at TRIUMF. Further, we will present ongoing applications of the NCSMC to 11C(p,p) scattering and the 11C(p,γ)12N radiative capture of relevance to astrophysics. Finally, we will show our preliminary results for the unbound and controversial 9He nucleus.

References:

Breakout D1
Recent Developments of the Gamow Shell Model for Nuclear Structure and Reaction

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Dripline nuclei exhibit different properties compared to those lying close to the valley of stability. The ground states of those systems can form halo structures or can even be unbound to particle emission. In fact, dripline nuclei are open quantum systems, for which the proximity of the continuum of unbound scattering states must be taken into account theoretically.

To this end, the Gamow Shell Model (GSM) has been successfully introduced to study loosely bound and resonant nuclear many-body states [1]. The GSM is rooted in the one-body Berggren basis, comprising bound, resonant and scattering states. The continuum degrees of freedom are thus included at basis level, and the configuration mixing between many-body basis states contributes to inter-nucleon correlations. For very large GSM matrices, where Lanczos and Davidson methods can no longer be used, the Density Matrix Renormalization Group (DMRG) has been introduced [2].

In order to use GSM to describe nuclear reactions, the Resonating Group Method (RGM) has been applied [3]. In the RGM method, a basis of channels is constructed from target and projectile states, which generate compound many-body basis states. Target states and projectile states are calculated in GSM, as they consist of bound or resonant eigenstates of the GSM Hamiltonian. Scattering wave functions and reaction cross sections can then be calculated. In this presentation, various GSM applications to structure and reactions of light nuclei will be presented. They include: 18Ne(p,p) [3] and 14O(p,p) [4] reactions, where the proton-rich 19Na and 15F nuclei are unbound, as well as 6Li(p,γ)7Be, 6Li(n,γ)7Li [5], 7Be(p,γ)8B, and 7Li(n,γ)8Li radiative capture reactions [6] of astrophysical interest.

References:
Breakout D1

Resonance and Continuum in Atomic Nuclei

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Resonance is a general phenomenon happening in classic or quantum systems. It plays a special role in weakly-bound or unbound quantum systems. An unbound quantum system, such as atomic cluster or unbound nucleus, can emerge in the form of intrinsic resonance. Starting from realistic nuclear forces, we have developed a core Gamow shell model which can describe resonance and continuum properties of loosely-bound or unbound nuclear systems. To describe properly resonance and continuum, the Berggren representation has been employed, which treats bound, resonant and continuum states on equal footing in a complex-momentum plane. To derive the model-space effective interaction from realistic forces, the full Q-box folded-diagram renormalization has been developed for the nondegenerate complex-momentum space. The CD-Bonn potential is softened by using the V_{low-k} method. Choosing O-16 as the inert core, we have calculated sd-shell neutron-rich oxygen isotopes, giving good descriptions of both bound and resonant states. The isotopes O-25 and O-26 are calculated to be resonant even in their ground states. Excited-state resonance spectra have been calculated and analyzed systematically for neutron-rich oxygen isotopes, compared with available experimental observations.

Breakout D1

Recent Progress in Building Novel Nonlocal Energy Density Functionals

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Numerous applications of nuclear DFT have shown a tremendous success of the approach, which by using a dozen-odd coupling constants allows for correct description of a multitude of nuclear phenomena. However, recent analyses indicate that the currently used models have probably reached their limits of precision and extrapolability. The question of whether these can be systematically improved appears to be one of the central issues of the present-day investigations in nuclear-structure theory. In this talk, I will present status of theoretical developments that aim to build novel nonlocal energy density functionals (EDFs).

In particular, we recently proposed [1] to use a two-body regularized finite-range pseudopotential to generate nuclear EDFs in both particle-hole and particle-particle channels, which makes them suitable for beyond-mean-field calculations. We derived a sequence of pseudopotentials regularized up to next-to-leading order (NLO) and next-to-next-to-leading order (N2LO), which fairly well describe infinite-nuclear-matter properties and finite open-shell paired and/or deformed nuclei. Solutions of the corresponding self-consistent equations were implemented in spherical and triaxial symmetries, codes FINRES4 [2] and HFODD [3], respectively.

In Landau theory of Fermi liquids, the particle-hole interaction near the Fermi energy in different spin-isospin channels is probed in terms of an expansion over the Legendre polynomials. In Ref. [4] we showed general expressions for Landau parameters corresponding to a two-body central local regularized pseudopotential and we showed results obtained for the two recent parametrizations NLO and N2LO, adjusted in Ref. [1].

In Ref. [5] we showed results of the Hartree-Fock-Bogolyubov calculations performed using these two parametrizations. We discussed properties of binding energies and pairing gaps determined in semi-magic spherical nuclei. The results were compared with benchmark calculations performed for the functional generator SLyMR0 [6] and functional UNEDF0 [7].

[1] K. Bennaceur et al., arXiv:1611.09311
Breakout D1

Fusion with Exotic Nuclei Using Microscopic Methods

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Fusion reactions are affected by nuclear structure and many dynamical processes. Some effects of internal nuclear structure on reactions such as heavy-ion fusion can be seen by studying features of experimental fusion barrier distributions. Until more recently, theoretical modelling of these reactions were largely of phenomenological nature. Whilst this approach is useful to start with and works very well for light stable systems, moving towards heavier and more exotic systems demands more powerful theory to be able to both describe processes observed experimentally and predict fusion cross sections for exotic nuclei. Upcoming exotic beam facilities provide motivation to understand reaction with neutron rich nuclei theoretically. Microscopic approaches based on energy density functionals (EDF) provide insightful tools to study heavy-ion reactions including fusion. The same EDF can be used to describe both structure and reaction properties on the same footing [1].

Based on this method, one can investigate reaction dynamics, such as near barrier fusion, with both stable and exotic nuclei [2,3]. We use both static and time-dependent versions of the EDF method to study the fusion reactions along isotopic chains. For instance, there are clear differences between potential barriers calculated with static and time-dependent Hartree-Fock methods.

A key result is that the dynamics plays a major role in the reaction, washing out static effects such as neutron skins which are expected to lower the bare potential barrier [2]. Instead, coupling to transfer channels, which have been studied microscopically in [3], is shown to play an important role.

References:

**Breakout C2**

**β -delayed Neutron Emission Studies for Heavy Isotopes**

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β-decay is the most common way for neutron-rich nuclei to reach the stability valley. However, when the neutron separation energy is lower than the Q_β-value, β-delayed neutron emission [1] takes over a dominant role in these β-decays, decreasing the mass of the nucleus by one unit (β1n) or more in the case of multiple neutron emission (β2n, β3n, ...). The study of the neutron branching ratios, P_n, is crucial for a better understanding of the astrophysical rapid neutron capture (r-) process where neutron emission can become dominant during freeze-out when the material decays back to stability. So far only a third of the around 600 accessible isotopes that are neutron emitters have been measured, the heaviest ones with masses up to A~150 [2], plus a single measurement for 210Tl [3]. Concerning multiple neutron emission, only 24 of the ~300 accessible isotopes have been measured up to mass A=100.

In this contribution the results of two recent measurements with the neutron detector BELEN [4] will be presented. A first experiment performed at the GSI Darmstadt (Germany) with the Fragment Separator allowed for the first time the determination of the P_1n values of several isotopes of Hg and Tl for masses beyond A>200 and N>126 [5]. A second experiment that took place at the IGISOL facility in Jyvaskyla (Finland) allowed to measure the heaviest β2n emitter identified so far, 136Sb. The resulting P_2n value is much smaller than previously assumed. In addition, the P_1n values of many important fission products in this mass region were remeasured with higher precision [6].

An outlook will be given about the BRIKEN campaign at RIKEN (Japan) which was commissioned in November 2016 and will start data taking in May 2017. BRIKEN aims to perform in the next years measurements for more than a hundred β1n-, dozens of β2n- and several β3n-emitters, lots of them for the first time and in the most exotic regions reached so far.

**References:**

Breakout C2

Gamma and Fast-timing Spectroscopy Around $^{132}$Sn From the Beta-decay of In Isotopes

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During the last two decades there has been a substantial effort directed to gather information about the region around the neutron-rich $^{132}$Sn [1]. Nuclei in the regions of shell closures with a large N/Z ratio such as $^{132}$Sn are of great interest to test nuclear models and provide information about single particle states. More stringent tests of the models can be provided by the reduced transition probabilities connecting nuclear states. In this work we have used fast-timing and gamma spectroscopy to study five Sn nuclei, including the doubly magic $^{132}$Sn, the two neutron hole $^{130}$Sn and two-neutron particle $^{134}$Sn, and the one-neutron hole $^{131}$Sn and one-neutron particle $^{133}$Sn. The Sn isotopes were studied at the ISOLDE facility, where their excited states were populated in the beta-decay of In isomers, produced in a UCx target unit equipped with a neutron converter. The In isomers were ionized using the ISOLDE Resonance Ionization Laser Ion Source (RILIS), which for the first time allowed isomer-selective ionization. The measurements took place at the new ISOLDE Decay Station (IDS), equipped with four highly efficient clover-type Ge detectors, along with a compact fast-timing setup consisting on two LaBr$_3$(Ce) detectors and a fast beta detector. The setup incorporated a tape transport system to remove longer-lived activities.

Indium isotopes with masses ranging from 130 to 134 were produced. The RILIS isomer selectivity made it possible to produce odd-mass In isotopes with a clean separation between the 9/2$^+$ and 1/2$^-$ beta-decaying isomers. For the even isotopes, such as $^{134}$In, it was also possible to separate the 5 heavier and 1-$^+$ isomers. We report on the lifetime of the 331-keV 1/2$^+$ level in $^{131}$In, which provides information on the M1 transition to the ground state and on its degree of forbiddenness, similar to what has been recently been measured in [2]. In addition we explore the presence of the h$_{11/2}$ single particle level at 65.1 keV[3] using coincidences. For $^{133}$Sn we discuss the identification of the 1363-keV level as the 2p$_{1/2}$ single-particle state, and on the search for the missing 13/2$^+$ state [4]. We also report on the search for the particle-hole multiplet states that have not been identified yet in the even Sn isotopes, in particular in $^{132}$Sn.

References:

Breakout C2

Gamow-Teller Decay of $^{74}$Co and Decay Properties of $^{78}$Co→$^{78}$Ni

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First experimental studies of the doubly magic nucleus $^{78}$Ni became possible [1,2] and are needed to provide critical data to test robustness of the nuclear shell structure and model the astrophysical r-process [3]. One way to study the structure of neutron-rich nickel isotopes ($Z = 28$) is to investigate decays of the respective cobalt precursors ($Z = 27$). This method has been successfully implemented in fragmentation-type experiments reaching the very exotic $^{77}$Co. While it is presently not possible to produce $^{78}$Co with sufficient rate to use it for studies of excited states in $^{78}$Ni, the decay measurements of $^{78}$Co will be possible with the new facilities under construction around the world and beam intensity upgrades. Nevertheless, information on the $\beta$ decay of the most neutron rich cobalt isotopes enables us to predict decay properties of $^{78}$Co to $^{78}$Ni. We will present new data on the decay of $^{74}$Co, which we use to extend the systematics on the decay of even-A cobalt isotopes to predict decay properties of $^{78}$Co.

Low-energy level structure of $^{74}$Ni was investigated through the $\beta$-decay of $^{74}$Co at the National Superconducting Cyclotron Laboratory (NSCL). The ions of $^{74}$Co were produced by projectile fragmentation of $^{82}$Se ions at an energy of 140 MeV/nucleon on a $^9$Be target. The particle identification was performed on an event-by-event basis by measuring energy loss ($\Delta E$) in a silicon detector placed in the beam line and time-of-flight (TOF) between focal planes. The separated fragments were implanted in a germanium double-sided strip detector [4]. The experimental data show existence of two $\beta$-branching states in $^{74}$Co based on observation of two $\gamma$-ray cascades populating low- and high-spin states in $^{74}$Ni. The origin of the decay is attributed to the strong Gamow-Teller transformation from $\nu f_{5/2}$ to $\pi f_{7/2}$. The systematics of the $B(\text{GT})$ strength distribution in neutron-rich cobalt isotopes and $N=51$ isotones indicate the robustness of the closed core in $^{78}$Ni. Predictions for decay properties of $^{78}$Co are made from the systematics and shell model calculations.

References:
Breakout C2

Beta-Decay and Mass-Measurement Studies of Deformed, Neutron-Rich Nuclei in the A~160 Region*

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Properties of deformed, neutron-rich nuclei in the A~160 region are important for achieving a better understanding of the nuclear structure in this region where little is known owing to difficulties in the production of these nuclei at the present RIB facilities. These properties are essential ingredients in the interpretation of the rare-earth peak at A~160 in the r-process abundance distribution, since various theoretical models depend sensitively on the nuclear structure input. Predicated on these ideas, we have initiated a new experimental program at Argonne National Laboratory. The first experiment recently took place where a combination of the CARIBU radioactive beam facility with the new SATURN decay station and the X-array clover array was performed. We focused initially on several odd-odd nuclei, where decays of both the ground state and an excited isomer were investigated. Because of the spin difference, a variety of structures in the daughter nuclei were selectively populated and characterized based on their decay properties. Results from these studies will be presented, including the first identification of beta-decaying isomers in both 160 Eu and 162 Eu, together with predictions using multi-quasiparticle blocking calculations that include the effect of the residual nucleon-nucleon interactions. Mass measurements using the Canadian Penning Trap aimed at measuring the excitation energy of the beta-decaying isomers were also carried out and new results will be also reported.

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Intruder States in Neutron Rich Phosphorus Isotopes Near $N=28$

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Understanding the evolution of shell structure as a function of N/Z is one main focus of current nuclear structure studies. The force behind the migration of orbitals is the monopole part of the tensor interaction. Refinement of this monopole term to increase the predictive powers of shell model calculations underscores the need for more experimental information, especially for excited states in exotic nuclei. Odd Z and odd-odd nuclei provide one of the most stringent tests of shell model predictions as many more degrees of freedom are available.

The structure of odd Z phosphorus isotopes ($N = 22 – 25$) were investigated at the National Superconducting Cyclotron Laboratory via the beta decay of Si isotopes. Following allowed beta decay, intruder states were populated in the P isotopes which could be identified based on the measured logft values. First gamma transitions in $^{38,40P}$ were observed de-exciting the strongly populated $1^+$ states. These $1^+$ states at relatively low energy (~2MeV) with parity opposite to the $2^-$ ground state are core excited $1p-1h$ states (1). The occurrence of intruder states at low energies highlights the importance of pairing and quadrupole correlation energies in lowering the intruder states despite the $N = 20$ shell gap. Configuration interaction shell model calculations with the state-of-art SDPF-MU effective interaction were performed to understand the structure of these $1p1h$ states in the even-$A$ Phosphorus isotopes. States in $^{40P}$ with $N = 25$ were found to have very complex configurations involving all the fp orbitals leading to deformed states as seen in neutron rich nuclei with $N \sim 28$. The calculated GT matrix elements for the beta decay highlight the dominance of the decay of core neutrons over the valence neutrons in neutron rich nuclei when neutrons and protons occupy shells of opposite parity. Unlike the even A isotopes, for the odd A isotopes the negative parity intruder states lie at higher excitation energies and the beta decay strength was found to be fragmented. Systematic discussion of the results for $^{37-40P}$ will be presented highlighting the effects of adding neutrons on the shell structure.

References:
1) V. Tripathi et al., accepted in PRC, 1/24/2017

This work was supported by NSF grants PHY-1401574 (FSU) and PHY-1068217 (NSCL), US DoE under contracts DEAC02-05CH11231 (LBNL) and DE-SC00098 (FSU) and JSPS KAKENHI (Japan), Grants No. 25870168 and 15K05094.
Shape Coexistence in Neutron-rich $^{31}$Mg Investigated by Beta-gamma Spectroscopy of Spin-polarized $^{31}$Na

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One of the long-standing subjects of nuclear physics is the shape transition of the ground state far from the beta-stability line. In particular, neutron-rich nuclei with neutron number close to the neutron magic number $N = 20$, so-called the “island of inversion”, have attracted much attention. In this mass region of the nuclear chart, it was suggested that the ground states are rather deformed, although these nuclei have a nearly-magic number of neutrons. In the recent theoretical studies [1, 2], not only the ground-state deformation but also shape coexistence were suggested in a low excitation energy region of nuclei in the island of inversion.

In the present work, we study on neutron-rich nucleus $^{31}$Mg ($N=19$). The level structure of odd-mass $^{31}$Mg is one of the most sensitive probe of shape coexistence, because the nuclear structure is strongly affected by the configuration of the last neutron. However, up to now, none of the spins and parities, which are the key quantities to understand the nuclear structure, were not firmly assigned except for the ground state. In such a situation, it is rather difficult to discuss the structure of $^{31}$Mg. In the present work, the detailed level structure of $^{31}$Mg is investigated by our extremely promising method [3] to assign spin-parity of excited states based on the beta-gamma spectroscopy of the spin-polarized $^{31}$Na.

The experiment was performed at ISAC in TRIUMF, where a highly polarized $^{31}$Na beam is available. Our method is successfully applied to the excited states of $^{31}$Mg, and the spins and parities of 5 levels in $^{31}$Mg are unambiguously determined by detection of the beta-ray asymmetry. The firm spin-parity assignments for the exited states enable us to compare with the theoretical calculations of the AMD+GCM framework [1] on level-by-level basis. It is found that the levels in $^{31}$Mg are categorized into three types of largely deformed rotational bands, states with spherical natures, and a state which cannot be explained by theoretical models at present. The recent shell model [2] also predicts the levels with the three different configurations below 1 MeV, and they are in good agreement with the experimental results. These facts provide clear evidence for the shape coexistence in a low excitation energy region of $^{31}$Mg.

References:
Breakout C2

Detailed Spectroscopy of Neutron-rich Sn Isotopes with GRIFFIN

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The region of neutron-rich tin isotopes near A = 130 is of great interest to nuclear structure. In particular, 132Sn with 50 protons and 82 neutrons represents a doubly magic nucleus and provides an essential benchmark for the shell model far from stability. Understanding the structure of this nucleus provides a foundation to comprehend the single-particle nature of excited states in neighboring isotopes. With no excited states below 4 MeV, 132Sn can be considered to be the most magic among heavy nuclei. Among known excited states, several particle-hole multiplets have been identified, as well as a collective 3+ level characteristic of doubly magic nuclei [1,2]. In addition to nuclear structure considerations, the region around 132Sn is also useful in astrophysics, as studying the properties of these nuclei is key to understanding the r-process path and its role in creating the A = 130 abundance peak.

The nucleus 132Sn has recently been studied as part of a campaign to investigate the structure of neutron-rich tin isotopes at the TRIUMF-ISAC facility. Excited states in 132Sn were produced from the beta-decay of 132In. A low-energy beam of 132In was delivered to the GRIFFIN experimental station [3], where the 16 high-purity germanium clovers were used to detect gamma-rays. In addition, SCEPTAR [4], an array of 20 plastic scintillators, was used to detect beta-particles to create beta-gamma-gamma coincident spectra. This experiment represents the most sensitive study of 132Sn to date, allowing for the identification of new weakly fed levels as well as confirmation of spin and parity assignments of several excited states via angular correlation measurements. In this talk, I will present new results on the levels in this nucleus as well as prospects for other Sn isotopes.

References:
Breakout C2

Decay Spectroscopy of Neutron-Rich Cd Around the N = 82 Shell Closure

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The neutron-rich Cadmium isotopes around A=130 are of special interest to both nuclear structure and astrophysics. Situated near the well-known magic numbers at Z=50 and N=82, these nuclei are prime candidates to study the evolving shell structure observed in exotic nuclei. Additionally, the extra binding energy observed around the nearby doubly-magic $^{132}$Sn has direct correlations in astrophysical models, leading to the second r-process abundance peak at A~130 and the corresponding waiting-point nuclei around N=82. The beta-decay of the N=82 isotope $^{130}$Cd into $^{130}$In was first studied a decade ago [1], but the information for states of the lighter indium isotope ($^{128}$In) is still limited. These motivating factors has led us to perform detailed γ-ray spectroscopy follow the beta-decay of $^{128-132}$Cd using the GRIFFIN [2] facility at TRIUMF, which is capable of performing spectroscopy down to rates of 0.1 pps.

The ongoing analysis of the $^{128,131,132}$Cd will be presented. Already in $^{128}$Cd, 23 new transitions and 15 new states have been observed in addition to the 4 previously observed excited states [3]. Its half-life has also been remeasured via the time distribution of the strongest gamma-rays in the decay scheme with a higher precision [4]. For $^{131}$Cd, results will be compared with the recent EURICA data. These data highlight the unique capabilities of GRIFFIN for decay spectroscopy on the most exotic, short-lived isotopes, and the necessity to re-investigate also "well-known" decay schemes for missing transitions.

References:
Breakout C2

Spying on Intruders in the $^{68}$Ni Region with Fast Timing

FRAILE, Luis M 1; OLAIZOLA, Bruno 2; GHITA, Dan 3; KÖSTER, Ulli 4; KURCEWICZ, Wiktor 5; LESHER, Shelly 6; PAUWELS, Dieter 7; PICADO, Esteba 8; RADULOV, Deyan 7; SIMPSON, Gary 9; UDÍAS, José 1; BOMANS, Pieter 7; POVES, Alfredo 10; BORCEA, Ruxandra 3; BORGE, María 11; CRESSWELL, John 12; DE WITTE, Hilde 7; FLAVIGNY, Freddy 7; FYNBO, Hans 13; GAFFNEY, Liam 7; GREENLEES, Paul 14; IBÁÑEZ, Paula 1; KONKI, Joonas 14; MACH, Henryk 15; KRÖLL, Thorsten 16; KURCEWICZ, Jan 11; LALKOVSKI, Stefan 17; LAZARUS, Ian 12; LIS, Razvan 11; LUND, Morten 13; MADURGA, Miguel 11; MARGINEAN, Nicolae 3; MARGINEAN, Raluca 3; MIHAI, Radu 5; SOTTY, Christophe 5; NEGRET, Alexandru 5; PAKARINEN, Janne 14; PASCU, Sorin 3; PÉREZ-LIVA, Mailyn 1; PUCKNELL, Vic 12; RAHKILA, Panu 14; RAPISARDA, Elisa 15; ROTARU, Florin 3; SWARTZ, Jacobus 7; VAN DUPPEN, Piet 7; TENGBLAD, Olof 18; VEDIA, Victoria 1; VIDAL, Marie 1; WALTERS, William 19; WARR, Nigel 20; HUYSE, Mark 7; APRAHAMIAN, Ani 21; BRIZ, José Antonio 11; CAL-GONZÁLEZ, Jacobo 22

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The nucleus $^{68}$Ni is the portal to the understanding of the modification of shell structure in the Z=28 and N=40 region and the appearance of collective phenomena. In spite of showing some of the characteristics of a doubly magic nucleus, the two-neutron separation energy does not show evidence for an enhanced N=40 harmonic oscillator shell gap, and collectivity emerges for $^{66}$Fe and $^{64}$Cr with just one and two proton pairs less than $^{68}$Ni.

The changes in shell structure around $^{68}$Ni are driven by excitations across the Z=28 and N=40 shell gaps, where the neutron $g_{9/2}$ and $d_{5/2}$ configurations and the proton $p_{3/2}$ orbital play a key role. This scenario provides the breeding ground for shape-coexistence. Indeed, several 0+ states have been observed in $^{68}$Ni below 3 MeV [1,2]. They can be explained in the framework of Monte Carlo shell model calculations [3], which yield prolate bands built on strongly deformed 0+ states appear for several eve Ni isotopes, and by multiple particle-hole excitations in the shell model framework [4]. A similar picture is observed for $^{66}$Ni, where three excited 0+ states have been identified [5]. The coexistence of configurations has been observed in the Z=27 Co isotopes, for which low-lying proton intruders have been reported in $^{65,67}$Co [6].

In this paper we investigate of intruder configurations via the fast timing ATD $\beta\gamma\gamma(t)$ measurement of excited level lifetimes in nuclei around $^{68}$Ni. The nuclides under study were populated in the beta-decay chains of Mn isotopes, strongly produced at ISOLDE on a UC x target, and selectively ionized by RILIS. We report on level lifetimes in $^{68}$Ni, in particular on investigation of the transition connecting the third 0+ with the first 2+, and compare it to the recent result by Crider et al. [4]. We provide information on the lifetime of the third 0+ 2671-keV level in $^{68}$Ni, and on the transition connecting it to the first excited 2+ level. We interpret these supposedly similar configurations in $^{68}$Ni and $^{66}$Ni in the shell model framework. We also investigate the role of proton intruders by examining the state at 1095 keV in $^{66}$Co, whose lifetime has also been measured.

References:
Charge Exchange Reactions of Unstable Nuclei and the Beta-Decay Strength

The Gamow-Teller transition (G-T) strengths are important for understanding nucleosynthesis in stars. The transition strength not only from a ground state but also from an excited state becomes important in some cases. Charge exchange reactions provide information of G-T strength even for transitions to excited states. However, such studies have been done only at around stable nuclei. Here we show the first measurement of charge exchange (p,n) reaction on C isotopes from A=12 to 19 and demonstrate the feasibility of such experiments.

In the present experiment, production cross sections of nitrogen isotopes from high-energy (~950 MeV per nucleon) carbon isotopes on hydrogen have been measured. The fragment separator FRS at GSI was used to deliver C-isotope beams. Since the production of nitrogen is mostly due to charge-exchange (Cex) reactions below the proton separation energies, the present data reveal Gamow-Teller and/or Fermi transition strength at low excitation energies for neutron-rich carbon isotopes. The window of a Cex reaction below the proton emission threshold and window of the beta-decay are very close with each other for neutron-rich nuclei because of the small neutron separation energy.

Comparisons of transition strength obtained by two methods were made for C isotopes, and consistent results were obtained for nuclei of which beta-strength are known. In light nuclei most of the transition is allowed and thus no complications due to forbidden transition are seen. The Cex cross section increases for more neutron-rich C isotopes indicating the increase of sum of the beta strength within the window. Since the two windows are almost the same for nuclei along the r-process path, studies of charge exchange reactions of r-process nuclei would provide information on the total strength of beta decay complementary with the half-life measurement in which decay strength are weighted by the decay energy of each decay channel. A simultaneous measurement of the neutrons and fragments is expected to give us more detailed information. Perspective and future experiments will be discussed in addition.

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The Gamow-Teller transition (G-T) strengths are important for understanding nucleosynthesis in stars. The transition strength not only from a ground state but also from an excited state becomes important in some cases. Charge exchange reactions provide information of G-T strength even for transitions to excited states. However, such studies have been done only at around stable nuclei. Here we show the first measurement of charge exchange (p,n) reaction on C isotopes from A=12 to 19 and demonstrate the feasibility of such experiments.

In the present experiment, production cross sections of nitrogen isotopes from high-energy (~950 MeV per nucleon) carbon isotopes on hydrogen have been measured. The fragment separator FRS at GSI was used to deliver C-isotope beams. Since the production of nitrogen is mostly due to charge-exchange (Cex) reactions below the proton separation energies, the present data reveal Gamow-Teller and/or Fermi transition strength at low excitation energies for neutron-rich carbon isotopes. The window of a Cex reaction below the proton emission threshold and window of the beta-decay are very close with each other for neutron-rich nuclei because of the small neutron separation energy.

Comparisons of transition strength obtained by two methods were made for C isotopes, and consistent results were obtained for nuclei of which beta-strength are known. In light nuclei most of the transition is allowed and thus no complications due to forbidden transition are seen. The Cex cross section increases for more neutron-rich C isotopes indicating the increase of sum of the beta strength within the window. Since the two windows are almost the same for nuclei along the r-process path, studies of charge exchange reactions of r-process nuclei would provide information on the total strength of beta decay complementary with the half-life measurement in which decay strength are weighted by the decay energy of each decay channel. A simultaneous measurement of the neutrons and fragments is expected to give us more detailed information. Perspective and future experiments will be discussed in addition.
Structure of Unbound Nuclei $^{10}\text{N}$ and $^{9}\text{He}$

Evolution of nuclear structure of Nitrogen isotopes ($Z=7$) and $N=7$ isotones with increasing imbalance between protons and neutrons has been a focus of intense scrutiny since the discovery of parity inversion in $^{11}\text{Be}$. Yet, the level structure of the most exotic nuclear systems with 7 neutrons or protons (such as $^{9}\text{He}$, $^{10}\text{Li}$, $^{10}\text{N}$) remain uncertain and presents a major challenge both theoretically and experimentally. Recent experimental results that shed light on the structure of $^{9}\text{He}$ and $^{10}\text{N}$ will be discussed.

The low-lying levels in $^{10}\text{N}$ (mirror of $^{10}\text{Li}$) have been populated in $^9\text{C}+p$ resonance scattering [1]. The location of the $2s_{1/2}$ shell in this most neutron deficient isotope of Nitrogen is now firmly established. Properties of the ground and first excited states of $^{10}\text{N}$ will be discussed.

The level structure of $^{9}\text{He}$ was studied through the $T=5/2$ isobaric analog states in $^9\text{Li}$, populated via $^8\text{He}+p$ resonance scattering [2]. No narrow $T=5/2$ structures were observed in the proton spectrum, providing strong evidence that there are no narrow, near neutron threshold states in $^{9}\text{He}$, suggested previously in several other experiments (see [3] and references therein).

The new experimental results provide a good basis for better understanding of shell evolution in $Z/N=7$ nuclear systems and for making reliable extrapolations on the structure of $^{10}\text{Li}$ and $^{9}\text{N}$ (never observed) isotopes.

References:
Direct observation of neutron-proton (np) correlations and 3N-force in nuclei is the long-sought goal in nuclear physics. Two-nucleon knockout reactions offer a powerful tool as the reaction cross section is a direct probe of nucleon correlations. The experimental data of $^{12}\text{C}$ on a carbon target reveal that the inclusive cross sections of residues from np removal channel ($^{10}\text{B}$) is approximately 6-8 times greater than those for nn pair (to $^{10}\text{C}$) and pp pair (to $^{10}\text{Be}$) [1,2], already in excess of the $16/6 \approx 2.7$ ratio from simple pair counting in $^{12}\text{C}$. Such enhancement however could not be described by the calculations using eikonal reaction dynamics and microscopic structure from the effective-interaction shell model and the no-core shell model with chiral NN+3N interactions [3].

To further investigate the nature of nucleon correlations and the origin of discrepancy between the observations and theories, we have performed the first final-state exclusive np-removal cross section measurements using DALI2 gamma-detection array and SAMURAI spectrometer at RIKEN. By the gamma-residue coincidence measurement, the partial cross sections to $^{10}\text{B}$ and $^{10}\text{Be}$ $T=0$ and $T=1$ final sates following np and pp removal from $^{13}\text{C}$ at 200 MeV/u were extracted. The experimental results indicate the insufficient treatment of $T=0$ np-correlations and 3N-force in the current microscopic structure models. In this talk, the experimental setup and the physics results will be discussed.

References:
Breakout D2

Neutrons Correlations in the Continuum of Two (core + 4n) Systems

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Nuclear correlations involved in neutron-rich nuclei, up to the drip line, play essential roles in the understanding and modeling of neutron captures in the r-process nucleosynthesis as well as in the understanding of phenomena linked to the neutron star superfluidity. They are also interesting in view of generalizing the Ikeda conjecture, commonly applied to alpha clusters, to dineutron clusters above the corresponding emission threshold. We have discovered a novel method that allows to reveal neutron correlations in the nucleus and to search for dineutron contribution. This was achieved by studying the decay of high energy states above $S_{2n}$ populated after the sudden knockout of a deeply bound nucleon. This sudden approximation, together with a quasi-free knockout process can reliably be assumed, owing to the high energy of the projectile used (440 MeV/u) during the experiment. This experiment, performed at GSI, required the complex and innovative R3B-LAND setup to determine the full kinematics of the reaction. My presentation will be focused on the n-n correlations observed in the decay of unbound states in the $^{18}$C and $^{20}$O (viewed as $^{14}$C+4n and $^{16}$O+4n, respectively) populated via the sudden knockout of a proton in $^{19}$N and a neutron in $^{21}$O, respectively. We have studied the evolution of the n-n correlations as a function of the increasing energy $E_d$ of the neutrons and compared the decay patterns of the two systems; i.e. the former, in which neutron pairs are in principle kept intact, and the second in which the $^{16}$O core is broken, leaving two unpaired neutrons. We used a simulation that takes into account the different decay mechanisms (direct, sequential and dineutron decay) and the final state interactions to interpret the experimental data. Using information on n-n and core-n momenta, we show that we can clearly distinguish direct from sequential decays. Remarkably, direct decays are strongly dominant in $^{18}$C up to $E_d=8$MeV, beyond which sequential decay amounts to only 20%. A very strong enhancement is found at small relative neutron momentum angles that is discussed in term of a dineutron component. This is in contrast to the case of $^{20}$O, in which sequential decays dominate already at low $E_d$, and in which much weaker n-n correlations are observed. Due to the success of this method, we are planning in a near future to extend such a study to other systems closer to the drip line and to generalize the study of neutron correlations to the 4n decay channel.
Evidence for Z=6 Subshell Closure in Neutron-Rich Carbon Isotopes

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The nuclear magic numbers, as we know in stable nuclei, consist of two different series of numbers. The first series – 2, 8, 20 – is attributed to the harmonic oscillator potential, while the second one – 28, 50, 82, and 126 – is due to the spin-orbit interactions. The spin-orbit interactions are known to be significant and responsible for the large (spin-orbit) splitting of the single-particle states in heavy nuclei. These interactions, however, are expected to diminish in light nuclei due to the low orbital angular momenta. This general expectation is supported by the fact that there is an apparent lack of fingerprints for a ‘magic number’ (subshell closure) at 6 or 14 [1], which might have arisen from the widening 1p1/2-1p3/2 and 1d3/2-1d5/2 gaps, respectively, in the stable nuclei. A possible subshell closure at N=6 has been suggested both theoretically [2] and experimentally [3] in the very neutron-rich 4He isotope. For Z=6 and 14, possible subshell closures have been suggested [4] in the semi-magic 14C and 34Si.

In this talk, we will present experimental evidence for a prevalent subshell closure at proton number Z=6 in the neutron-rich carbon isotopes. We investigated (i) the proton density distribution radii, combining our recent data for Be, B and C isotopes measured at RCNP, Osaka University and GSI, Darmstadt, with the available data from Ref. [5]; (ii) the atomic masses [6]; and (iii) the electromagnetic transition strengths [7] for a wide range of isotopes. Our systematic analysis revealed marked regularities which support a prominent proton ‘magic number’ Z=6 in 13−20C.

References:
Breakout D2

Direct Measurements of \((\alpha,p)\) Reactions with ANASEN

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The LSU-FSU Array for Nuclear Astrophysics and Structure with Exotic Nuclei (ANASEN) has been developed, in part, for the direct measurement of \((\alpha,p)\) reactions with radioactive beams. It is currently installed at the John D. Fox Superconducting Accelerator Laboratory at FSU. The ANASEN detector consists of position-sensitive proportional counter aligned with the beam axis surrounded by a barrel-shaped array of double-sided silicon strip detectors. Utilizing an active gas target, ANASEN is able to measure the excitation function of reactions through a range of energies relevant to astrophysics.

Recently, two measurements on neutron-deficient \(N=8\) nuclei were made with ANASEN. Both measured reactions are important to the understanding of Type-I X-ray bursts. Sensitivity studies of reaction network calculations indicate that the rate of the \(^{18}\text{Ne}(\alpha,p)^{21}\text{Na}\) reaction plays an important role in breakout into the rp-process from the hot CNO cycles in Type-I X-ray bursts [1,2]. The rate of the \(^{17}\text{F}(\alpha,p)^{20}\text{Ne}\) reaction has significant influence on both the output light curve and the composition of ashes in multi-zone X-ray burst model calculations [3]. The results of these measurements will be presented.

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References:


Breakout D2

Investigation of \(^{198}\text{Hg}\) and \(^{199}\text{Hg}\) Through Direct Reactions for the Interpretation of EDM Limits

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The observation of a large permanent electric dipole moment (EDM) would represent a clear signal of CP violation from new physics outside the Standard Model. The \(^{199}\text{Hg}\) isotope currently provides the most stringent limit on an atomic EDM, which is converted to a limit on the nuclear EDM via a calculation of the Schiff moment. To do this knowledge of the nuclear structure of \(^{199}\text{Hg}\) is required. Ideal information to further develop and constrain the \(^{199}\text{Hg}\) Schiff moment nuclear structure theoretical models are the E3 and E1 strength distributions to the ground state, and E2 transitions amongst excited states. The high level density of \(^{199}\text{Hg}\) makes those determinations extremely challenging, however similar information can be obtained from exploring surrounding even-even Hg isotopes. One of the most direct ways of measuring the E3 and E1 matrix elements is through inelastic hadron scattering, and single-nucleon transfer reactions on targets of even-even isotopes of Hg can yield important information on the single-particle nature of \(^{199}\text{Hg}\).

As part of a campaign to study the Hg isotopes, a number of experiments have been performed using the Q3D spectrograph at the Maier-Leibnitz Laboratory, with 22 MeV deuteron beams impinging on enriched Hg\(^{32}\text{S}\) targets. The first experiment accesses the E2 and E3 matrix elements in \(^{198}\text{Hg}\) via inelastic deuteron scattering. We measured 9 angles ranging from 10 to 115 degrees up to an excitation energy of 5 MeV. The second set of measurements discussed will be single-nucleon transfer reactions, \(^{198}\text{Hg}(d,p)^{199}\text{Hg}\) with spin-parity assignments and spectroscopic factors extracted through distorted-wave Born approximation calculations with global optical model parameter sets.
**Breakout D2**

**Quasi-free Proton Knockout Reactions on the Oxygen Isotopic Chain**

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According to the Independent Particle Model (IPM), single-particle (SP) states are fully occupied up to the Fermi energy with spectroscopic factors (SF) of one. However, it is well known from electron-induced proton knockout that the SP strength is reduced to about 60-70% for stable nuclei, which has been attributed to the presence of short- and long-range correlations [1]. This finding has been confirmed by nuclear knockout reactions using stable and exotic beams, however, with a strong dependency on the proton-neutron asymmetry [2]. The observed strong reduction of SP cross sections for the deeply bound valence nucleons in asymmetric nuclei is theoretically not understood. To understand this dependency quantitatively a complementary approach, quasi-free (QF) knockout reactions, is introduced. QF knockout reactions in inverse kinematics at relativistic energies provide a direct way to investigate the SP structure of stable and exotic nuclei [3].

We have performed a systematic study of spectroscopic strength of oxygen isotopes using QF (p,2p) knockout reactions in complete kinematics at the R3B/LAND setup at GSI with secondary beams containing $^{13-24}\text{O}$. The oxygen isotopic chain covers a large variation of separation energies, which allow a systematic study of SF with respect to neutron-proton asymmetry.

We will present results on the (p,2p) cross sections for the entire oxygen isotopic chain obtained from a single experiment. By comparison with the Eikonal reaction theory [4] the SF and reduction factors as a function of separation energy have been extracted and will be compared to existing data in literature. The results include total and partial cross sections extracted by means of gamma-coincidence measurements as well as momentum distributions. The latter are sensitive to the angular momentum of the knocked-out nucleon in the projectile.

Finally, a brief report will be given on a pioneer experiment performed at RIKEN where the QF (p,2p)-fission reaction was employed for the first time on $^{238}\text{U}$ as a benchmark test for future applications to determine fission barriers of neutron-rich exotic nuclei near $^{208}\text{Pb}$ and $^{214}\text{Bi}$.

This work is supported by the GSI-TU Darmstadt cooperation agreement and the BMBF Verbundforschung under contract 05P15RDFN1.

**References:**

Breakout D2

Study on the Isoscalar Excitation of the Pygmy Dipole Resonance in $^{68}$Ni

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Recently, much relevance has been given to the collective states in neutron-rich nuclei. The remarkable interest in these states is driven by the presence of an electric dipole response around the nucleon binding energy [1,2]. This mode, the so called Pygmy Dipole Resonance (PDR), although is carrying few per cent of the isovector Energy Weighted Sum Rule (EWSR) has a strong relation with the symmetry energy and it has been used as a further tool to constrain it. It is predicted to be present in almost all nuclei with neutron excess: in particular for nuclei far from the stability line. This mode can be populated by both isoscalar and isovector probes due to the properties of its transition densities [3]. Several experiments, with both the probes, have been performed on stable nuclei [1,2,4,5]. Whereas, the study of the PDR with unstable nuclei has been done in pioneering experiments carried out at the GSI, using relativistic Coulomb excitations on $^{132}$Sn [6] and $^{68}$Ni [7] isotopes.

We use, for the first time, an isoscalar probe to excite the PDR on an unstable isotope. The experiment with a $^{68}$Ni beam at 33 MeV/nucleon on a $^{12}$C target was performed at LNS-INFN of Catania. The unstable beam was produced by In Flight Fragmentation method in a dedicated In Flight Radioactive Ion Beams (FRIBs) transport line. The detector systems CHIMERA [8] and Farcos [9] were used to detect both gamma and charged products.

References:

Plenary Friday

Applications of $\beta$-radiation Detected NMR in Wet Chemistry, Biochemistry and Medicine

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Many physiological processes in nature are governed by the interaction of biomolecules with metal ions. Some biologically highly relevant metal ions, such as $\text{Mg}^{2+}$, $\text{Cu}^+$ and $\text{Zn}^{2+}$, are silent in most spectroscopic techniques leaving wide gaps in understanding their biological functions. Therefore, there is the need for finding new experimental approaches to directly study these metal ions.

Recently, $\beta$-radiation detected nuclear magnetic resonance ($\beta$-NMR) spectroscopy was successfully applied to liquid samples at the ISOLDE and ISAC facilities at CERN and at TRIUMF, Canada’s national laboratory for particle and nuclear physics, respectively. This marks an achievement, which opens new opportunities in the fields of wet chemistry. In contrast to earlier measurements, the resonance spectra of $^{31}\text{Mg}^+$ implanted into different ionic liquid samples, recorded at ISAC, showed highly-resolved resonances originating from Mg ions occupying different coordination geometries, illustrating that $\beta$-NMR can in fact discriminate between different structures – the first and very important step towards the applications of this technique in biochemistry and medicine. Recorded resonance line widths are comparable or even narrower than the ones in conventional NMR spectroscopy on similar systems, underlining the complementarity and advantages of $\beta$-NMR. After these successful tests, a new spectrometer for bio-$\beta$-NMR experiments is currently under construction at TRIUMF’s $\beta$-NMR facility, which will allow for experiments not only on different samples, such as gels, and liquids, but also at different vacuum environments ($10^{-7}$ mbar - 50 mbar).

Results from the recent $\beta$-NMR experiments with $^{31}\text{Mg}^+$ ions performed at TRIUMF, the former tests at the ISOLDE, as well as future plans will be presented and discussed.

Plenary Friday

Keeping up the Standards: Applying New Nuclear Decay and Structure Data for Radionuclide Metrology

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The radioactivity group based at the UK’s National Physical Laboratory (NPL) is responsible for traceability of radiological standards and sources. This work requires the use of a range of novel and high-precision radiation detection systems which can be utilised to provide definitive standards of the stoichiometry, decay rate and physical nature of emissions from different samples of radioactive materials. The link in the unbroken calibration chain for measurements of activity concentrations of radiopharmaceuticals and other radioactive sources / reference materials is based at the NPL, which is responsible for the ultimate traceability to the Becquerel (Bq) within the UK.

This talk will outline some of the experimental techniques which are used to provide primary and secondary standards for radioactivity calibrations based on gamma-ray and/or charged particle spectrometry and highlight the importance of robust, evaluated nuclear data in such underpinning applications. An example of the recent standardisation of the naturally occurring isotope $^{223}\text{Ra}$ [1,2] will be presented. This is of particular current focus as this radionuclide is both a member of the actinium (4n+1) decay chain headed by $^{235}\text{U}$ and also the main therapeutic component in the radiopharmaceutical XOFIGO® [3]. The presentation will also outline some of the other methods for the production and radiochemical separation of $^{236}\text{Np}$ as a long-lived tracer for $^{237}\text{Np}$ via ICP - Mass spectrometry measurements in nuclear waste management [4]. Finally, progress on the use of a digitally-based system for primary standardisations of $^{60}\text{Co}$ and $^{134}\text{Cs}$, using coincident gamma-ray spectroscopy using LaBr$_3$(Ce) detector modules (the NANA spectrometer) will be presented [5].

Plenary Friday

Understanding of Decay Heat and the Reactor Anti-neutrino Spectrum Using Total Absorption Spectroscopy

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Total Absorption Spectroscopy is a unique technique characterized by high efficiency detection of gamma-ray radiation. This property, used in the study of beta decay of unstable nuclei, allows for the total detection of the deexcitation path of daughter nuclei. This makes it an ideal technique to establish the true beta-decay feeding pattern, especially for the decays of nuclei suffering from the Pandemonium Effect [1]. Recent studies show that the measurements of fission products by total absorption spectroscopy are extremely important to understanding the decay heat and anti-neutrino spectrum emitted from nuclear reactors [2]. Decay heat is determined on the basis of the average energy of gamma and beta radiation emitted in the beta decay of fission products. Incomplete knowledge of the decay schemes, in particular, omission of beta transitions to high-excited states, causes an underestimation of the electromagnetic part of the decay heat and a revaluation of the beta component. This was observed by comparison with direct measurements [3]. The solution is to measure the beta decay of fission products using high-efficiency systems such as total absorption spectrometers.

The number of reactor anti-neutrino interactions measured by inverse-beta decay detectors is about 6% smaller than the expected number of events, which is named the reactor anti-neutrino anomaly [4]. The anti-neutrino energy spectrum, obtained from the fission product beta-decay schemes, is used to calculate the total anti-neutrino flux emitted by reactor cores and the number of anti-neutrino interactions with the detector matter. The measurements of the beta decay of fission products using the total absorption technique allow verification of the expected number of interacting reactor anti-neutrinos with matter.

In this contribution we present several results of total absorption spectroscopy measurements of the beta decay of nuclides abundantly produced in the reactor core. The measurements were performed at the Holifield Radioactive Ion Beam Facility (HRIBF) with the Modular Total Absorption Spectrometer (MTAS), the largest total absorption spectrometer in the world. The results and their impact on the decay heat and anti-neutrino spectra reconstruction will be presented and discussed.

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Plenary Friday

Tree-Ring-Dating of Millennial Climate Change Across Southern Africa with AMS

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High-resolution palaeoclimate records that might contribute to testing climate models are rare and often they are inadequately resolved in terms of their chronology or the precision of the proxy. Combining disparate evidence has yielded a rainfall record for the last 200 years that is suggestive but has large errors associated with it. This record reconstructs a drying trend that is contrast with the model reconstructions and forecasts for the region of Southern Africa. In addition the high-resolution rainfall record derived from tree rings in Zimbabwe does not reflect the same interannual variability for records from the Limpopo River Valley.

This research project has obtained 1000-year isotopic tree ring records that are duplicated in each of the major climate regimes in southern Africa. This was readily achieved as the existing inventory of trees that are immediately available for analysis offers high level of coverage. Tree ring analysis is a promising technique to accomplish this in terms of rainfall, but it emerges that most of the long-lived tree species in southern Africa form irregular rings that prevent the use of traditional ring analysis. It is possible to calibrate the tree isotope records at the level of precision that is required.

Among the tree species that demonstrably proxy palaeoclimates through isotopes, there are key species that are both long-lived and their distribution covers the main target sampling areas. The A.eerioloba trees cover the more arid part of the subcontinent and they have been shown to grow to more than 1000 years in age. The southern limit of the baobab distribution represents the East/West transect that is desired, and a recent study on the age of baobabs has demonstrated that they can achieve ages in the order of 2000 years. The Podocarpus trees are from wetter areas including coastal and mountain forests and they have also been demonstrated to grow in excess of 1000 years. The conclusion that may be drawn from this is that it is feasible that a stable light isotope palaeoclimate for the broader southern African landscape may be derived from isotopic analysis of tree rings. The ring structures have been identified and their chronology is under establishment through application of radiocarbon dating at iThemba LABS with the Accelerator Mass Spectrometry (AMS) facility. The ring counting and radiocarbon chronologies will be reconciled to provide the absolute dates for the individual isotope measurements.
Plenary Friday

Charting New Ground with ISOLTRAP: A Survey of Recent Nuclear Binding-energy Studies

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In the last years the main experimental approach to the complex nuclear many-body problem has been to track the variation of nuclear properties with the number of protons and neutrons. This justifies the ever-growing number of radioactive ion beam experiments and the great importance of binding energies, which are among the first observables reaching into unexplored regions of the nuclear chart. Their trends are sensitive to a wide range of nuclear-structure phenomena of single-particle or collective type and hence they constitute, for virtually every model, an essential input quantity.

In pioneering the techniques of on-line Penning-trap mass spectrometry, the ISOLTRAP experiment [1] at ISOLDE/CERN has dedicated many years of research to the study of exotic systems at various frontiers of the nuclear chart. In this work some of the most recent results will be presented. The masses of neutron-rich cadmium isotopes around $^{130}$Cd are an incursion into the effect of the $N = 82$ magic number below the tin isotopic chain and its impact on $r$-process nucleosynthesis [2], while the masses of neutron-rich copper isotopes up to $^{69}$Cu give important insight into the evolution of the $Z = 28$ and $N = 50$ “shell closures” and the double magicity of $^{68}$Ni. Midway between magic numbers, the masses of strontium, rubidium and krypton isotopes beyond $N = 60$ delineate the “nuclear-shape transition” in the region of nuclides of mass $A = 100$. Most of these new measurements have demonstrated the importance of ISOLTRAP’s multi-reflection time-of-flight mass spectrometer (MR-TOF MS) [3], either as beam purifier or as mass-measurement apparatus. Since its implementation in the ISOLTRAP setup the MR-TOF MS has become a versatile beam-analysis tool. The variety of applications of the MR-TOF MS, as well as recent advances in the implementation of the phase-imaging ion-cyclotron-resonance technique [4] at ISOLTRAP, will be presented.

References:
Plenary Friday

The Rare-RI Ring Ready to Explore Terra Incognita

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The Rare-RI Ring at the RIBF/RIKEN facility has been recently commissioned and is now ready to start its mission of measuring masses of extremely rare isotopes. The unique location of the Rare-RI Ring at the RIBF/RIKEN facility presents an extraordinary chance to measure nuclear masses in the Terra Incognita. These nuclear masses are of particular importance in understanding the synthesis of chemical elements via the r-process but also crucial in understanding nuclear structure far from stability.

The Rare-RI Ring is based on the Isochronous Mass Spectrometry technique that allows reaching a mass measurement precision of $10^{-6}$ in less than 1 ms. Therefore, making mass measurements of extremely short-lived nuclei with low production yields possible. The full operation of the Rare-RI Ring has been achieved in three commissioning stages. In this contribution, the three commissioning experiments will be summarized and the current performance will be presented. Finally, the perspective of our physics program will be shown.

Plenary Friday

Recent Mass Measurements for Nuclear Astrophysics at JYFLTRAP

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JYFLTRAP is a cylindrical double Penning trap mass spectrometer [1] located at the Ion Guide Isotope Separator On-Line (IGISOL) [2] facility in Jyväskylä. In total, over 330 atomic masses for nuclear structure, fundamental physics and nuclear astrophysics have been measured with JYFLTRAP. In this contribution, I will focus on recent mass measurements for nuclear astrophysics obtained after the recommissioning of JYFLTRAP at the IGISOL-4 facility in 2014.

In the neutron-deficient side, $^{31}$Cl [3] and $^{52}$Co [4] are among the most exotic nuclei ever studied at JYFLTRAP. Their masses are important for testing the isobaric multiplet mass equation as well as for the rapid proton capture (rp) process occurring e.g. in type I X-ray bursts. The new, more precise proton separation energy for $^{31}$Cl helps to constrain astrophysical conditions where $^{30}$S can act as a waiting point in the rp process. We have also improved the precisions of proton-capture Q-values relevant for calculating the proton-capture rates for two key reactions, $^{25}$Al(p,g)$^{26}$Si and $^{30}$P(p,g)$^{31}$S [5]. Accurate knowledge of the reaction rates is needed for more reliable calculations of the amount of cosmic 1809-keV gamma rays and abundances of intermediate-mass elements in novae, respectively. In the neutron-rich side, we have recently extended our studies to the heavier fission-fragment region relevant for understanding the formation of the rare-earth peak in the astrophysical r-process.

References:

Plenary Friday

Nuclear Structure Studies Based on Energy Density Functionals

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The self-consistent nuclear mean-field framework based on universal energy density functionals provides an accurate description of ground-state properties and collective excitations over the entire nuclear chart, from relatively light to super-heavy nuclei, and from the valley of beta-stability to the particle drip-lines. Based on this framework, structure models have been developed that go beyond the mean-field approximation and take into account collective correlations related to restoration of broken symmetries and fluctuation of collective variables. These include the generator-coordinate method with projections on particle number, angular momentum and parity, the collective Hamiltonian for quadrupole and octupole degrees of freedom, the microscopic interacting boson-fermion model. Among the most interesting recent applications of this framework are studies of shape evolution and shape-phase transitions: the occurrence of rigid triaxial deformations, quadrupole and octupole shape transitions in rare-earth nuclei and light actinides, and signatures of shape transitions in odd-mass nuclei.

Plenary Friday

Presentation by Poster Award Winner

Instrumentation for the SPES Facility

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The SPES Radioactive Ion Beam facility at INFN-LNL is presently in the construction phase. The facility is based on the ISOL method with an UCx Direct Target able to sustain a power of 10 kW. The primary proton beam is provided by a high current Cyclotron accelerator with energy of 35-70 MeV and a beam current of up to 0.75 mA. Neutron-rich radioactive ions are produced by proton induced Uranium fission at an expected fission rate of the order of $10^{13}$ fissions per second. After ionization and selection the exotic isotopes are reaccelerated by the ALPI superconducting Linac at energies of 10 AMeV. The key feature of SPES is to provide high intensity and high-quality beams of neutron rich nuclei to perform forefront research in nuclear structure, reaction dynamics and interdisciplinary fields like medical, biological and material sciences. New instrumentation is required for operation with unstable beams and needs to be implemented coherently with the relevant milestones of the facility. Non-reaccelerated beams will be used for beta decay studies aided by the state of the art setup planned to this purpose. Reaccelerated beams, making use of direct reactions, will exploit magnetic spectrometers coupled to gamma array. The Galileo gamma spectrometer is being implemented to this purpose. An early phase of Galileo is presently operating with stable beams, selected preliminary results will be presented. For the operation with the first reaccelerated beams the AGATA tracking array will be installed at Legnaro in conjunction with a variety of ancillary detectors. A superconducting solenoid is planned to be used in conjunction with an active target and a high resolution missing mass spectrometer is under study in order to allow simultaneous measurement of excitation and de-excitation energy. Some examples of physics opportunities will be discussed.
Advances in Radioactive Isotope Science / Book of abstracts

Plenary Friday

High-intensity Superconducting ECR Ion Source SECRAL

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RIB accelerator requests high power primary ion beam which actually very much depends on performance of the front-end ion source. SECRAL (Superconducting Electron Cyclotron Resonance ion source with Advanced design in Lanzhou) is a superconducting-magnet-based ECRIS (Electron Cyclotron Resonance Ion Source) for the production of intense highly-charged heavy ion beams. It is one of the best performing ECRISs worldwide and the first superconducting ECRIS built with an innovative magnet to generate a high strength Minimum-B field for operation with heating microwaves up to 24-28 GHz. SECRAL has so far produced a good number of CW (Continuous Wave) intensity records of highly-charged ion beams, in which the beam intensities of $^{40}$Ar$^{12+}$ and $^{129}$Xe$^{26+}$ have exceeded 1 emA for the first time by an ion source. The great performance of SECRAL is accumulation of a number of technical advancements, such as the innovative magnet structure for better plasma confinement and more effective double-frequency (24+18 GHz) heating with an optimized 24 GHz wave coupling to operate at higher wave power with improved plasma stability. SECRAL source has run into operation to deliver highly charged ion beams for HIRFL accelerator for more than 9 years and total beam time more than 30000 hours, which has demonstrated its excellent stability and reliability. This talk will present the innovative magnet structure and the latest development of SECRAL ECR ion source.

Plenary Friday

Production of N = 126 Nuclei and Beyond Using Multinucleon Transfer Reactions for KISS Project

WATANABE, Yutaka, Mr. KAKIGUCHI, Yutaka; Prof. MIYATAKE, Hiroshi; Prof. DEFRANCE, Gilles; Prof. ALAHARI, Navin; Dr. REJMUND, Maurycy; Dr. SCHMITT, Christelle; Prof. POLLAROLO, Giovanni; Prof. CORRADI, Lorenzo; Dr. FIORETTO, Enrico; Dr. MONTANARI, Daniele; Dr. NIKURA, Megumi; Dr. SUZUKI, Daisuke; Mr. OYAIZU, Michihiro; Dr. NISHIBATA, Hiroki; Mr. TAKATSU, Jun; Mr. MURAD, Ahmed; Dr. MOON, Jun Young; Dr. PARK, Jin Hyung; Dr. WATANABE, Yutaka; Dr. KIM, Yung Hee; Dr. SCHURY, Peter; Dr. ISHIYAMA, Hironobu; Dr. JUNG, Hyosoon; Prof. WADA, Michiharu; KIMURA, Sota; Ms. MUKAI, Momo; Prof. CHOI, Seonho; Dr. SONG, Jeong Seog; Dr. CLEMENT, Emmanuel

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Multinucleon transfer (MNT) reaction between two heavy ions at energies around the Coulomb barrier is considered as a promising candidate to produce and investigate exotic nuclei. It is expected to provide a mean to efficiently produce especially neutron-rich nuclei around the neutron magic number of 126, which is difficult to access by other production methods.

The nuclear region of the neutron magic number N = 126 has been attracting an astrophysical interest because it is the waiting point nuclei on the r-process path, which are considered as progenitors of the peak at the mass number of 195 in the solar r-abundance distribution.

We have constructed the KEK Isotope Separation System (KISS) at RIKEN RIBF facility to produce, separate and measure the nuclear properties of those neutron-rich nuclei around the neutron magic number N = 126, which will be produced by the MNT reaction. KISS consists of an argon gas cell based laser ion source and an isotope separation on-line (ISOL), to produce pure low-energy beams of neutron-rich isotopes around N = 126 and to study their beta-decay properties.

We adopted the reaction system of $^{136}$Xe + $^{198}$Pt, which is considered to be one of the best candidates to efficiently produce the nuclei of interest. In order to investigate the feasibility of the nuclear production of the system, we have studied the collisions between $^{136}$Xe and $^{198}$Pt at the laboratory energy of 8 MeV/nucleon by using the EXOGAM gamma-ray array coupled to the large acceptance magnetic spectrometer VAMOS++ at GANIL.

In this presentation, we will show the experimental results of nuclear production by the $^{136}$Xe + $^{198}$Pt reaction system, where the promising potential of the production of new isotopes around and beyond the neutron shell N = 126 by MNT reactions were demonstrated. We will discuss about the production of those nuclei using MNT reactions at KISS.
Plenary Friday

Charge Breeding Techniques for European Facilities

Dr. TRAYKOV, Emil ¹; Mr. CAM, Jean François ²; Dr. SHORNIKOV, Andrey ³; Mr. ANNALURU, Arun ¹; Dr. DELAHAYE, Pierre ³; Dr. MAUNOURY, Laurent ³

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In the frame of two European collaborative projects, EMILIE and ENSAR 2, the charge breeding techniques are being improved.

While SPIRAL 1 at GANIL and SPES will use an ECR charge breeder, ISOLDE is upgrading its charge breeder. The two techniques present different advantages and drawbacks which were thoroughly studied during the past decade.

The ECR charge breeder has recently benefited from different upgrades. As an example, the SPIRAL 1 charge breeder has reached a new level of performances with its upgraded vacuum, injection / extraction optics and RF coupling. Better understanding of the capture process could be obtained. Despite these progresses, the observed behavior of the charge breeding time as a function of the support gas and plasma parameters raises new questions. This behavior is presently being studied by simulation before new on-line data is obtained with the SPIRAL 1 charge breeder.

Efficient acceleration of medium mass (A>40) to heavy ions to high energy requires the use of a highly performing EBIS charge breeder. ISOLDE is presently working on the improvement of the EBIS electron optics, making use of a new high-compression gun at low energies and high current and large trapping capacities. While EBIS charge breeders provide the highest charge states, the pulsed structure of the Highly Charged Ion (HCI) beam makes their use cumbersome for many experiments. The EMILIE debuncher has been constructed at LPC Caen for an easy manipulation of the longitudinal phase space of the HCI beam to match the needs of the experiments. The availability of fast and high repetition rate ion production in combination with debunching technology allows to build a versatile and flexible injection system for various linac- and cyclotron-based post acceleration schemes.

Plenary Friday

Towards A Single Atom Microscope for Nuclear Astrophysics

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We are developing the technique of optically detecting individual atoms embedded in thin films of cryogenically frozen solids. Noble gas solids such as frozen neon are an attractive medium because they are optically transparent and provide efficient, pure, stable, & chemically inert confinement for a wide variety of atomic and molecular species. The excitation and emission spectra of atoms embedded in solids can be separated by up to hundreds of nanometers making optical single atom detection feasible. We propose to couple a single atom microscope (SAM) detector to a recoil separator with the goal of measuring rare nuclear reactions relevant for nuclear astrophysics. The recoil separator would minimize the heat load on SAM while allowing for isotope discrimination. This technique has the potential to capture and detect every product atom with near unity efficiency. Because of the additional selectivity provided by resonantly exciting the atomic transitions of the captured product atom, SAM would have a negligible false positive rate which would help loosen the often demanding beam rejection requirements imposed on recoil separators. Our primary focus and long term goal is to measure the Ne-22(He-4,n)Mg-25 reaction, an important source of neutrons for the s-process, in the astrophysically relevant center-of-mass energy regime. We will describe the SAM concept in more detail, some of the critical technical challenges, and our progress towards demonstrating optical single atom detection of atoms embedded inside of solid neon.
ARIS 2017
Poster Contributions
As of May 16, 2017
**Poster ID: 8**

**New Mass Spectrometry Results Since ARIS 2014: Can We (Again) Nominate “Ion Trap of the Year”?**

Mass measurements give us the nuclear binding energy, a fundamental property that is indispensable for the study of nuclear structure, stellar nucleosynthesis and neutron-star composition, as well as atomic and weak-interaction physics. The dedicated mass-measurement programs at all major nuclear-physics installations on the planet are excellent testimony to the relevance of masses.

The series of ENAM meetings from 1995 to 2008 highlighted the rise and subsequent dominance of Penning traps in the field of mass spectrometry. This dominance has continued through the new era of the ARIS meetings with another type of ion trap now coming into play: the mirror-reflection time-of-flight mass spectrometer (MR-TOF MS). In this presentation, we will briefly review and compare the ion-trap installations at radioactive beam facilities worldwide. We will then examine the wealth of new mass data and highlight the new physics results of the various programs. As for the previous ARIS conferences [1,2], we will propose a nomination for “trap of the year.”

http://iks32.fys.kuleuven.be/indico/event/0/session/15/contribution/270/material/slides/1.pdf

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**Poster ID: 11**

**An Analysis of Cross-sections of $^{11}$Li + $^{28}$Si Interaction in the Framework of the Double-folding Model**

Measurements of the angular distributions of the differential cross sections of elastic and inelastic scattering on different targets give important information about the surface structure of nuclei. It is believed that information about the halo structure, especially on the proton and neutron density distributions can be obtained by studying the elastic scattering at different energies and on different targets. Therefore, the study of the scattering of light of cluster ($^{6}$Li, $^{9}$Be) and exotic weakly bound nuclei ($^{4}$He, $^{11}$Li, $^{11}$Be, $^{17}$B) is of great interest. In recent years, $^{11}$Li nucleus attracted attention of both experimenters and theorists more than any other light nuclei, because it is the most prominent representative of the nuclei with a halo. An analysis of the experimental results aimed at studying of elastic and inelastic scattering of nuclei – the processes most sensitive to the geometric dimensions of the nuclei (the density distribution of nucleons in the nucleus) and their potential interactions – as a rule, uses both macroscopic and microscopic approaches. To obtain information about the nucleus structure it is necessary to gain a detailed knowledge of the mechanism of nucleus-nucleus interaction, which includes construction of nucleus-nucleus optical potentials.

In the present research the experimental data on the differential cross sections for elastic scattering of $^{31}$Li ions on $^{28}$Si nucleus at the energy of 29 MeV/nucleon were analyzed in the framework of the double-folding model using the Paris NN-potential CDM3Y. A good agreement with the experimental angular distributions of differential cross sections for elastic scattering was obtained and the values of the total reaction cross sections were calculated. From the analysis of experimental data on the interaction of $^{11}$Li ions with $^{28}$Si nucleus, the trend behavior of the energy dependence of total reaction cross sections at the low sub-barrier energies were predicted.

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Light Weakly Bound Helium and Lithium Nuclei: Peculiarities of Their Interaction at Energies Close to the Coulomb Barrier

A local increase in the cross section in the energy range (10 – 30) MeV/nucleon [1, 2], in the excitation functions of the total reaction cross sections ($\sigma_R$, TCS) was first experimentally detected in ($^6$He, $^9$Li) + $^{28}$Si reactions. Although no peculiarities are observed in the $R(E)$ dependence at high energies, in the low-energy range abnormally large values of $R(E)$ at the energies close to the Coulomb barrier ($B_c$) are registered for light weakly bound nuclei, which can be explained by the appearance of a variety of reaction channels. Of special interest are such effects for $^{11}$Li having small binding energy with its cluster components and a very low threshold energy for its decay into ($^9$Li + 2n), ($^{10}$Li + n).

To determine even greater effect, it is necessary to carry out experimental investigations of $R(E)$ for the interactions of ($^6$He, $^8$He, $^{11}$Li) nuclei with the light weakly bound target nucleus (H, Be, Be and others) at low energies. In this case, the "bump" must be even larger both in the cross section and in a broader energy range, and it may even appear at sub-barrier energies, i.e., the lower left boundary of the "bump" can move into the energy range below $B_c$. The detected large TCS values in the $R(E)$ dependence as well as its rapid increase in the low-energy range cause release of a large amount of energy, which is interesting from the viewpoint of search for fundamentally new energy sources of the future. A similar example is well known for dp-reactions where in the deep sub-energy region a significant increase in the cross-section, the so-called Oppenheimer-Phillips resonance [3] caused by the polarization of the weakly bound deuteron, is observed. This phenomenon was used in the thermonuclear reaction, accompanied by an enormous release of energy. In the case of reaction with $^6$He and $^{11}$Li (compared with the deuteron) this effect is more pronounced due to the lower binding energy, greater Coulomb repulsion forces causing polarization of these nuclei, low threshold of the decay energy and large positive values of Q-reactions.


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Isomeric State Mass Measurement and Identification at TITAN

For both nuclear structure and nuclear astrophysics, precision mass measurements of short-lived nuclei are required. The measurements made in the region surrounding the N=82 closed shell represent a region where each nuclide tests and improves our understanding of the nuclear shell model. The N=82 region is also where the paths of the astrophysical r-process come closest to the valley of beta-stability, so measurements here directly probe a process which is mostly inaccessible to RIB physics. Furthermore, mass measurements made far from the valley of beta-stability test the predictions of mass models used to perform astrophysical calculations while helping to constrain and improve future iterations of those mass models.

The TITAN facility at TRIUMF in Vancouver, Canada has recently measured the masses of several neutron-rich isotopes of $^{125-127}\text{Cd}$ near the N=82 closed neutron shell along with the masses of isomers of the odd-\textit{A} nuclei to precisions of 10 keV/c\textsuperscript{2} and lower. In all cases where an isomeric mass was measured, the ISOL beams produced at TRIUMF’s ISAC facility contained a cocktail of both the ground and isomeric state. When both states are present they were measured simultaneously and thus the definitive energy separation between the two states was measured. Of particular note is the first precision mass measurement of the $^{127}\text{Cd}$ ground state as until now, the isomer has been misidentified as the ground state.

While we are able to unambiguously assign isomeric energy separations as a result of these measurements, the spin of these states is often ambiguous and assigned based on systematics from lower mass isotopes and mirror nuclei. To address this ambiguity, we are preparing a new campaign of measurements that takes advantage of a collaboration with TRIUMF’s laser spectroscopy experiments to make simultaneous mass and laser spectroscopy measurements of the same cocktail beam. Thus the states and isomer can be assigned without question.

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Isochronous Mass Measurement of Low-lying Isomers around Doubly Magic $^{100}\text{Sn}$

Isomers have taken a center stage in nuclear physics as they provide useful information to study the nuclear structure properties. Isomers usually indicate the significant change in nuclear structure, especially for the isomers around the doubly-magic or semi-magic nuclei. We have performed an experiment of isochronous mass spectrometry to measure the projectile fragment of $^{112}\text{Sn}$ at the "southwest" region around $^{100}\text{Sn}$ near the proton dripline. A new isomeric state of $^{95}\text{Pd}$ was discovered for the first time, and the excitation energy of the new isomer is also determined experimentally. The $J^\pi$ of the newly-discovered isomer is predicted to be $1/2^-$, which can be understood as the excitation of valence proton from the $\pi 2p_{1/2}$ to $\pi 1g_{9/2}$.

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Investigating Quantum Phase Transition Behavior near the N=60 Critical Point in $^{94}$Sr Using the Recoil Distance Method

The neutron-rich Sr and Zr isotopes are characterized by a sudden onset of quadrupole deformation at neutron number N=60. This abrupt change in ground state shape as a function of neutron number N has been identified as an example of a Quantum Phase Transition (QPT) from a spherical phase to a deformed phase [1]; this onset of deformation from $^{96}$Sr to $^{98}$Sr has been observed in a recent Coulomb excitation measurement [2]. While the emphasis is usually put on the phase transition behavior at N=60, it is equally surprising that there is no enhancement of collectivity when adding up to 8 neutrons beyond the N=50 shell closure, which points to the robustness of the Z=38 proton sub-shell closure in the Sr isotopes. This delay of the onset of collectivity was first observed following the measurement of extremely low B(E2;2$^+\rightarrow 0^+$) values of less than 0.020 e²b² from $^{96}$Sr to $^{98}$Sr [3] which are an order-of-magnitude less than those observed for $^{98,100}$Sr [4]. Theoretical calculations for the Sr isotopes have been performed using a variety of approaches, and while these calculations reproduce the onset of deformation in Sr qualitatively, they differ on the details of the deformation parameters. A high-precision lifetime measurement of the 2$^+$ state in N=56 $^{94}$Sr has been performed to elucidate whether the onset of collectivity at N=60 is as sudden as generally assumed. The present measurement utilized the Recoil Distance Method implemented via the TIGRESS Integrated Plunger [5] and unsafe Coulomb excitation in inverse kinematics at TRIUMF's ISAC-II facility. Due to limited statistics imposed by the use of a radioactive $^{94}$Sr beam, a likelihood ratio $\chi^2$ method was derived and used to compare experimental data to Geant4 simulations. The measured lifetime of 7.7(4) ps is approximately 25% shorter than the previous result and the relative error has been reduced by a factor of approximately 8. A summary of the experiment and a comparison to existing theoretical models will be presented.


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New Short-lived Isotope $^{223}\text{Np}$ and the Non-existence of the $Z = 92$ Subshell Closure near $N = 126$

The $N=130$ short-lived isotope $^{223}\text{Np}$ was produced as evaporation residue (ER) in the fusion reaction $^{40}\text{Ar} + ^{187}\text{Re}$ at the gas-filled recoil separator Spectrometer for Heavy Atom and Nuclear Structure (SHANS). It was identified through temporal and spatial correlations with alpha-decays of $^{215}\text{Ac}$ and/or $^{211}\text{Fr}$, the third and fourth members of the alpha-decay chain starting from $^{223}\text{Np}$. The pileup signals of ER($^{223}\text{Np}$)-alpha($^{223}\text{Np}$)-alpha($^{219}\text{Pa}$) were resolved by using the digital pulse processing technique. An alpha decay with half-life of $T_{1/2} = 1.67^{+0.84}_{-0.42}$ microseconds and energy of $E = 9489(35)$ keV was attributed to $^{223}\text{Np}$. Based on the reduced alpha-decay width, spin and parity of $9/2^-$ were proposed for the ground state of $^{223}\text{Np}$, in agreement with large-scale shell-model calculations. This assignment together with the proton separation energy disprove the existence of a $Z=92$ subshell closure. In addition, two new alpha lines were observed in the alpha-decay of $^{223}\text{U}$ as the fine structures. Based on the hindrance factors extracted, spins and parities were assigned to the new excited states in the daughter nucleus $^{219}\text{Th}$. The structure evolution of $N=129,131$ isotones from Po to U will be discussed.

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Isospin Symmetry in the Lower sd Shell: Coulomb Excitation Study of $^{21}\text{Mg}$

Nuclei around the N=Z line serve as a way to investigate the level to which isospin symmetry is conserved in nature. Traditionally isospin symmetry and its breaking have been investigated by comparing the energies of excited states in mirror nuclei or their masses. In order to further the understanding of isospin symmetry breaking effects and develop the existing nuclear models, a range of spectroscopic data is required, including B(E2) values, in addition to level energies and nuclear masses. A recent publication by A. Wendt et al. [1] demonstrated that mirror energy differences of T=3/2 sd shell mirror pairs and the B(E2) values of T=1,2 nuclei are reasonably well reproduced by the modified USD interaction [2]. However, the available information on the B(E2) values of the neutron-deficient Tz=-3/2 nuclei was limited to the recently reported value of $^{33}\text{Ar}$ [1].

In July 2016, isospin symmetry was investigated in the lower sd shell by studying the Tz=-3/2 nucleus $^{21}\text{Mg}$ at TRIUMF-ISAC II. Excited states in $^{21}\text{Mg}$ were populated in Coulomb excitation (Coullex) reactions on $^{196}\text{Pt}$ and $^{110}\text{Pd}$ targets. Gamma rays originating from the projectile and target excitations were detected with the TIGRESS Ge array. Scattered particles were detected with the BAMBINO Si array. The aim was to measure the previously unknown B(E2; 1/2+ $\rightarrow$ 5/2+) value in $^{21}\text{Mg}$ and to get a second data point for the Tz=-3/2, B(E2) systematics. The $^{21}\text{Mg}$ experiment utilized digital sampling of Ge and Si detector waveforms. Recorded traces were fitted offline to improve the timing resolution of the measurement setup. This allowed the half-life of the first excited 1/2+ state in $^{21}\text{Mg}$ to be measured. The B(E2; 1/2+ $\rightarrow$ 5/2+) values extracted from the half-life value and from Coulex cross-section analysis performed with the GOSIA code are in very good agreement.

The first direct observation of the gamma-ray transition depopulating the first excited 1/2+ state in $^{21}\text{Mg}$ and two independent measurements of the B(E2; 1/2+ $\rightarrow$ 5/2+) value will be presented. The recent USD calculation, which predicts a large deviation in the B(E2) values between the mirror partners at mass A=21, will be compared to the newly obtained experimental data.

**SPEDE: Exploiting Conversion Electron Spectroscopy with Radioactive Ion Beams**

In-beam spectroscopic techniques have long been an invaluable tool in interpreting the complex structure of the nucleus and γ-ray spectrometers have long been one of the most important tools available to physicists. In recent years γ-ray spectrometers have been employed to exploit the new areas of the nuclear landscape made accessible through radioactive ion beams.

One such setup is the MINIBALL [1], which has been coupled to HIE-ISOLDE at CERN. In many regions of the nuclear chart conversion-electron emission competes with and even exceeds γ-ray emission as the main mechanism for electromagnetic decay.

Alongside this E0 transitions, which are common in nuclei exhibiting shape coexistence, can only proceed via conversion-electron emission. To maximise the potential of experiments studying these nuclei, coupling γ-ray spectrometers to other detector systems can give more information than either could alone.

The newly developed SPectrometer for Electron Detection (SPEDE) [2-4] consists of a segmented silicon detector in close proximity to the target for detection of conversion electrons and also accommodates a CD detector [5] employed for particle identification. SPEDE has been coupled to the MINIBALL γ-ray spectrometer at the upgraded HIE-ISOLDE facility at CERN.

The primary aim of SPEDE is to study octupole collectivity and shape coexistence [6–8]. Here will be presented details of this new experimental tool and results from the recently completed commissioning at HIE-ISOLDE. Alongside this a user-oriented simulation package that has been developed using the NPTool framework [9] will be detailed.


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The (\(^6\)Li,\(^6\)Li\') Reaction: A New Probe for Selecting Isovector Spin-flip Excitations in the Inelastic Channel

A recent measurement at the Research Center for Nuclear Physics in Osaka, Japan has been performed in which the novel (\(^6\)Li,\(^6\)Li\') reaction at 100 MeV/u was utilized, and wherein pure spin and isospin flip excitations in the inelastic channel (\(\Delta S=\Delta T=1, \Delta Tz=0\)) have been identified. This reaction channel was selected by tagging the de-excitation gamma rays with \(E_g=3.56\) MeV from the outgoing \(^6\)Li ejectile. With this technique we plan to extract inelastic strengths for Gamow-Teller and Spin-Dipole excitations in \(^{12}\)C as well as other measured nuclei. As these strengths are the primary ingredient of inelastic neutrino-nucleus scattering cross-sections, the (\(^6\)Li,\(^6\)Li\') reaction probe provides an alternative approach to measuring otherwise difficult to study neutrino-nucleus interactions. In this talk, I will present preliminary results of the experimental data, and outline this probes effectiveness and role in neutrino-nuclear astrophysics.

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MassExplorer: A Website for Nuclear Theory Calculations (massexplorer.frib.msu.edu)

For theoretical nuclear physics to gain a comprehensive and quantitative understanding of all nuclei it is necessary to develop a framework where meaningful calculations can be made throughout the nuclear chart. Such a framework has been established: using nuclear Density Functional Theory along with massively parallel computing, it is now possible to analyze and predict the global nuclear properties of any type of nucleus, from stable to short-lived and from light to superheavy species.

The website MassExplorer has been created to share the results of our large-scale mass table calculations which employ the framework described above. Currently it houses calculations for thousands of nuclei with even numbers of protons and neutrons, as well as approximations for the binding energies of even-odd and odd-odd nuclei. These tables can be downloaded directly and contain information on various ground state nuclear properties. The website also contains software which plots this data, allowing for a visual analysis of trends between nuclei. The calculations from this website were recently used in two projects: one concerning mass uncertainties and their impact on the astrophysical r-process [1] and another investigating the charge radii of neutron deficient iron isotopes [2]. MassExplorer will also soon display the results of our mass table calculations which incorporate reflection- asymmetric nuclear deformations, highlighting which nuclei possess such a shape and where such deformations are most prevalent on the nuclear chart.


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Development of a Low Energy Branch for the MARA Separator

The MARA Low-Energy branch is currently under development at the Univ. of Jyväskylä. The facility will be focused on the study of ground-state properties of exotic proton-rich nuclei employing in-gas-cell and in-gas-jet resonance ionisation spectroscopy, and will provide mass measurements of nuclei at the N=Z line of particular interest to the astrophysical rp process.

MARA-LEB will couple the recently commissioned MARA vacuum-mode mass separator [1] with a gas cell combined with an ion guide system for stopping, thermalising and transporting reaction products to the experimental stations. The mass selectivity of MARA, combined with the elemental selectivity achieved through laser ionisation within the gas cell, will open the way to the study of nuclei with production cross-sections several orders of magnitude smaller than isobars produced in the same nuclear reaction. Isotopes at or close to the N=Z line, for example light Ag and Sn isotopes, are of key interest. However, reliable experimental data on their ground-state properties are not available due to the absence of a technique which can be used for their efficient production and separation.

The gas cell is based on the concept developed at Leuven [2] and designed for the S3-LEB facility, GANIL. It will be able to use both Ar and He buffer gases to allow for more efficient neutralisation or faster extraction times respectively. Laser ionisation will be possible using a dedicated Ti:Sapphire laser system either in the gas cell or in the gas jet. Following extraction from the cell the ions will be transferred by radiofrequency ion guides and accelerated towards a magnetic dipole for further mass separation before transportation to the experimental setups.

In the first phase of the project a detector setup will be used for the characterisation and commissioning of the gas cell. Important information related to ionisation density in the gas and the effect on neutralisation will be studied, of direct interest to S3-LEB. In the second phase the gas cell will be combined with a laser ionisation spectroscopy setup and in the third phase with an MR-TOF-MS [3] which is currently being designed at IGISOL.

This presentation will focus on the status of the design and development of the facility.

References:

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A New On-line Surface Ion Source for TRIGA-TRAP: Design and First Results

The TRIGA-TRAP experiment is a double Penning-trap mass spectrometry experiment [1], located at the research reactor TRIGA Mainz. It is optimized for high-precision model independent measurements of the nuclear mass, which is directly related to the nuclear binding energy and Q-values. Its accurate knowledge is thus an excellent test of nuclear mass models. Nuclear masses of exotic nuclei are also of fundamental interest for nuclear structure and reaction studies.

TRIGA-TRAP gives access to isotopes produced in two different ways: (i) An off-line laser ablation ion source using a frequency doubled Nd-YAG laser provides transuranium ions from carefully prepared samples. (ii) Online coupling to the research reactor offers the possibility to measure short-lived nuclides produced by neutron-induced fission of U-235 or Cf-249 targets located near the reactor core.

Fission products are extracted by an aerosol-based gas-jet system and are guided through a skimmer system to a surface ion source. An aerodynamic lens [2] is installed to collimate the particles embedded in the gas-jet to maximize the injection efficiency into the ion source. The latter consists of a tantalum ionizer surrounded by two tungsten filaments and heat shields for efficient heating [3]. Thereby, temperatures above 2000 °C can be reached by electron bombardment. The produced ions are accelerated to 30 keV and mass separated in a 90° dipole magnet. Afterwards a radio-frequency quadrupole cooler/buncher [4] generates short bunches of low energy ions suitable for injection into the Penning trap.

Major upgrades have been implemented recently and will be discussed at the conference: A new surface ion source has been successfully implemented in collaboration with JAEA/Tokai, as well as new ion optics and an on-line monitoring detector.

References:
Collectivity Beyond N = 50 in Neutron-rich Kr and Se Isotopes

There has been a significant amount of both experimental and theoretical effort in the past decade to understand the evolution of collectivity in the region of the nuclear chart beyond the N = 50 shell closure [1]. The 38Sr and 40Zr isotopes display an almost constant small B(E2; 0^+→2^+) value from N = 48 to N = 56. There is a rapid increase in collectivity in these nuclei beyond N = 60 due to the proton-neutron quadrupole interaction between the g9/2 proton intruder configuration and the g7/2 neutrons beyond the N = 56 subshell closure [2]. There is evidence that the lower-Z isotopes 34Se and 36Kr exhibit a more smooth onset of deformation approaching N = 60. An intermediate-energy Coulomb excitation experiment was performed at the National Superconducting Cyclotron Laboratory to extract reduced quadrupole transition strengths, B(E2; 0^1→2^1+) for 88,90Kr and 86Se using the CAESAR γ-ray detection array [3] coupled with the S800 magnetic spectrograph [4]. This will allow us to determine the evolution of collectivity approaching N = 60 for Kr and Se, to provide a benchmark for theoretical calculations, and to reduce the large uncertainties of previously reported measurements of 90Kr [5] and 86Se [6]. The current status of the analysis and preliminary results will be presented.


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Towards Precision Mass Measurements and In-source Laser Spectroscopy of Neutron-deficient Silver Isotopes

The radioactive neutron deficient silver isotopes around the N=Z region have been of considerable interest for several years. In particular, N=Z $^{94}$Ag may exhibit the most unique isomer in existence. In addition to a low-spin (7$^+$) beta-delayed-proton decaying isomer, $^{94}$Ag has been identified as having a spin trap isomer with the highest spin, (21$^+$), ever observed for β-decaying nuclei. The isomer’s long half-life of 0.39(4) s [1], high excitation energy [2] and high spin [3] are matched by an unparalleled selection of decay modes including, among others, β decay [3] and one-proton [4] decay. However, the claimed existence of the most exotic form of decay in $^{94m}$Ag(21$^+$), namely two-proton emission, has been questioned [5]. One piece of the puzzle is the energy of the isomer. Mass measurements of $^{92}$Rh and $^{94}$Pd, the respective two-proton and β-decay daughters of $^{94}$Ag, have been performed at JYFLTRAP which, when combined with the original spectroscopic decay data, lead to a 1.4 MeV contradiction in the deduced isomer energy [6].

A project is underway at the Accelerator Laboratory of the University of Jyväskylä aiming to investigate the neutron-deficient isotopes of silver. The project will commence with the resonance ionization spectroscopy (RIS) of $^{101-97}$Ag, produced using the $^{92}$Mo($^{14}$N,2pxn)$^{104-x}$Ag heavy-ion fusion-evaporation reaction in order to extract and confirm the nuclear spins and magnetic dipole moments measured at KU Leuven [7]. The ultimate goal is a high precision mass measurement study in the region of the isotope $^{94}$Ag, aimed for direct measurements of $^{93}$Pd (the 1 proton decay channel), $^{94}$Ag and $^{94m}$Ag(21$^+$) masses in order to unambiguously determine the energy of isomer. We present the status of the project which has seen the commissioning of an inductively-heated hot cavity catcher [8], a device to be used in the production of silver isotopes. Recent results and new ion source developments will be discussed.


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Analysis on Three-body Problems with Gamow Coupled-channel Method

Background: Since the first use of rare isotope beams (RIBs) to analyze halo nuclei, more and more exotic structures and properties have been found in these weakly bound and unbound systems. And the physics behind such open quantum systems (OQSs) have attracted a lot of attention. However, for the reasons that such OQSs are often accompanied with configuration mixing and continuum effects, these regions remain a challenge for theory study.

Purpose: To describe such OQSs, we developed a 3-body Gamow coupled-channel (GCC) approach in Jacobi coordinates with Berggren basis. We benchmark it with the Gamow shell model (GSM) and regular coupled-channel (CC) calculations by studying energies and neutron correlation of halo nucleus He-6 and other $A=6$ nuclei.

Methods: We write our Hamiltonian and wavefunctions in Jacobi coordinate which includes T-type and Y-type configurations at same time, and the center-of-mass motion can be eliminated automatically. In our coupled-channel equations, we use hyperspherical harmonics to describe the angular part, and expand the radial wavefunction into Berggren ensemble which fully considers continuum effects and exhibits the correct asymptotic behavior at large distances.

Results: We show that the GCC method is both accurate and robust. The results are in good agreement with the calculations of GSM and regular CC method for the energy and radii of He-6. And we are trying to use this new method to analyze the newly discovered resonance state of O-26 and its decay mode.

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NUSTAR Perspectives at GSI and FAIR

NUSTAR is the largest collaboration for nuclear structure, astrophysics and reactions studies in the world. Over the last decade a versatile suite of state-of-the-art detection systems has been developed for the future FAIR facility. NUSTAR relies primarily on the availability of exotic rare isotope beams from FAIR produced by fragmentation reactions and fission of relativistic heavy ions at the fragment separator Super-FRS.

With the consolidation of the FAIR planning, NUSTAR experimental programmes in phases were agreed on. Phase-0, focuses on experiments starting in 2018 with the GSI accelerators upgraded to powerful FAIR injectors coupled to the fragment separator FRS. NUSTAR Phase-0 will take advantage of the versatile suite of state-of-the-art detection systems already developed and available. The novel experimental setups planned and in preparation will be discussed as well as exciting, unique examples for NUSTAR physics. NUSTAR perspectives for the Phase-1 programme at the final FAIR facility will be highlighted.

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Searching for Octupole Deformation in Neutron-rich Ba Isotopes at the CARIBU Facility

Octupole deformation and collectivity arise due to strong correlations when both protons and neutrons occupy single-particle orbitals near the Fermi surface with orbital (l) and total (j) angular momenta differing by $3\hbar$. Octupole-deformed nuclei have been predicted to exist in the lanthanide ($A \sim 146$) and actinide ($A \sim 224$) mass regions. The low-spin structure of the neutron-rich Barium isotopes plays an important role in differentiating between static and dynamic deformation. The decay schemes of several Barium isotopes have recently been extended with the X-Array and SATURN decay station at the CARIBU radioactive beam facility at Argonne National Laboratory. Isotopes of $^{142,144,146}$Ba were studied and the level schemes considerably expanded following $\beta$-decay of Cesium [1-3], and the decay schemes of odd-$A$ $^{143,145}$Ba are currently under analysis. The results of these decay studies will be extensively discussed and placed in the context of recent and planned multi-step Coulomb excitation experiments [4] that they complement.

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**Computational Design of Solid Stoppers for Generating Intense Re-accelerated Radioactive Ion Beams at FRIB**

Low-emittance beams of rare isotopes at low energies (less than 3 MeV/u) are required for many high precision measurements including nuclear mass measurements with Penning traps, laser spectroscopy, nuclear decay studies, and direct measurements of thermonuclear reactions that cause some stars to explode. Such beams will be produced at the Facility for Rare Isotope Beams (FRIB) by first slowing down and thermalizing or stopping the fast beams, and subsequently reaccelerating them to the desired energies for experiments. Solid stoppers offer great potential in providing high-intensity reaccelerated beams of many species. To design a solid stopper that can provide sufficiently prompt and efficient release of short-lived radionuclides, we are carrying out simulations of the critical processes including beam heating, diffusion release, and effusion transportation. We are using the COMSOL Multiphysics software [1], combined with LISE++ [2] and separate analytical calculations, to investigate the viability of a number of solid stopper systems for use at FRIB.


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**Oblate Deformation in $^{118,119}$Ag**

High spin states of $^{118,119}$Ag have been established for the first time by analyzing the high statistics gamma-gamma-gamma and gamma-gamma-gamma-gamma coincidence data from the spontaneous fission of $^{252}$Cf at Gammasphere. Two bands in $^{118}$Ag and two bands in $^{119}$Ag have been identified. Spins and parities are tentatively assigned according to the systematic comparison. A total Routhian surface calculation and projected shell model calculation have been performed to understand the behavior of these two nuclei. There is good agreement between the calculated level energies and experimental data. The calculations indicate oblate shape in $^{118,119}$Ag.

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**Poster ID : 93**

**Giant Resonances in $^{16}$N**

Charge-exchange experiments at intermediate energy yield important information about collective excitations with spin-isospin degrees of freedom. The properties of isovector giant resonances in neutron-rich rare-isotopes provide stringent tests of theoretical models and are important inputs for modeling of astrophysical phenomena.

The $(p,n)$ charge-exchange reaction in inverse kinematics has been developed as a new tool for investigating isovector giant resonances in rare isotopes. A $^{16}$C$(p,n)$ experiment at 100 MeV/u aimed at extracting isovector giant resonance strengths, in a neutron-rich isotope, up to high excitation energies was performed as a test case.

The Low Energy Neutron Detector Array (LENSA) and the Versatile Array of Neutron Detectors at Low Energy (VANDLE) were utilized in combination with the Ursinus Liquid Hydrogen Target and the S800 spectrograph to perform this experiment. The low-energy neutron that recoils from the target was detected by LENDA and VANDLE, while the fast beam-like ejectiles were detected in the S800 spectrograph. Results will be shown.

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**Poster ID : 95**

**Superallowed $\beta$ Decay of $^{26}$Si: A Sensitive Test of Isospin Symmetry-breaking Corrections**

We have measured the branching ratio for the superallowed $0^+ \rightarrow 0^+$ positron-emitter $^{26}$Si. Since the QEC value, 4840.86(10) keV, and half-life, 2245.3(7) ms, are known precisely, the branching ratio is all that is required to obtain a precise $\beta$ value.

This will complete the second pair of mirror superallowed transitions from a $T_z = -1$ parent, $^{26}$Si $\rightarrow$ $^{26m}$Al and $^{26m}$Al $\rightarrow$ $^{26}$Mg. A previous measurement of the mirror transition, $^{38}$Ca $\rightarrow$ $^{38m}$K and $^{38m}$K $\rightarrow$ $^{38}$Ar, showed that the ratio of mirror $\beta$-values is very sensitive to the model used to calculate the small isospin symmetry-breaking corrections required to extract $V_{ud}$. In calculating this correction, both Woods-Saxon and Hartree-Fock radial wave functions have been used, with the experimental results from the first pair favoring Woods-Saxon. The result for the $A = 26$ mirror pair will determine whether this conclusion can be generalized.

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Evaluation of New Chamber for Measurement of Total Kinetic Energy of Fission

Results of an upcoming evaluation of a new device for measurement of Total Kinetic Energy of fission in concert with the Gammasphere high purity Ge array will be detailed. The chamber is expected to be capable of obtaining Time of Flight (TOF) resolution close to 0.4 ns, allowing fragment velocity measurements with an accuracy of ~1.3 - 2.0 %, depending on which group of fragments are detected. Assuming a 40 kBq {superscript}252 Cf source, ~3 × 10⁴ s⁻¹ trigger signals are expected from the proposed chamber. This will result in trigger signals labeled with data on the fragment TOF and emission angle at a rate of ~1.8 × 10³ s⁻¹. Fragment velocities and angle of fission axis will be collected as part of the data, with respective uncertainty ≪ 2% and ≪ 8% (FWHM). Furthermore data for the amplitudes of gamma-ray signals from Gammasphere within ~100 ns after a fission-fragment trigger signal will be collected.

The need for Doppler broadening correction for gamma-rays emitted by moving fragments will decrease the precision of the resolution from ~2.5 keV, expected resolution for Gammasphere HPGe for energies of 200-1000 keV, to 3.5 and 5.0 keV for 500 and 1000 keV gamma peaks, respectively. No such correction will be needed for gamma-rays emitted by the complementary fragment, which would be stopped in the source backing.

The data provided will be useful towards investigating: Scission point deformation, Excitation energy spectra of fission fragments set in after scission at infinity, odd-even effects in the proton/neutron numbers of fission fragments obtained before neutron evaporation, temperature displayed at the scission point by the ensemble of internal degrees of freedom, angular momentum spectra of fission fragments, orientation of fragment spin in respect to the fission axis, and temperature acquired by the ensemble of dipole vibrations and oscillations bearing fragment angular momentum. We will also measure the angular distribution of gamma-rays with respect to the fission fragment axis, the correlation effects are expected to be very large. These data will be especially helpful for acquiring new insights in the low cross section level diagrams of Pm, Sm, Kr and Rb nuclei. Additionally simulation results for the chamber, based upon the use of the GEANT4 transport code with spontaneous fission modeled by FREYA as part of the LLNL Fission Library, will be presented.

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New Analysis of Levels in $^{96,100}$Y

Excited states of neutron rich $^{96,100}$Y have been studied by analyzing the high statistics gamma-gamma-gamma and gamma-gamma-gamma-gamma coincidence data from the spontaneous fission of $^{252}$Cf at Gammasphere and also from the prompt gamma-rays in coincidence with isotopically-identified by mass- and Z- fission fragments using VAMOS++ and EXOGAM at GANIL by using $^{238}$U beams on a $^{9}$Be target at energies around the Coulomb barrier. New transitions and new levels in $^{96}$Y and $^{100}$Y have been identified. Spins and parities are tentatively assigned according to the systematics.

A small deformation with near spherical shape is proposed for $^{96}$Y. A well deformed excited rotational band is also seen for the first time in this nucleus. Shell model calculations have been performed for $^{96}$Y and the levels are well reproduced. Bands in $^{100}$Y are proposed to have large deformation parameter ($\beta_2=0.45$). Two of the new bands in $^{100}$Y can form a $4^+ \pi_5/2[422]+\nu_3/2[411]$ and $5^+ \pi_5/2[422]+\nu_5/2[413]$ neutron pseudo spin doublet and two bands are proposed to form a $1^+ \pi_5/2[422]+\nu_3/2[411]$ and $4^+ \pi_5/2[422]+\nu_3/2[411]$ Gallagher-Moszkowski doublet. This is the first case where both such bands are seen in the same nucleus. Particle rotor model and triaxial covariant density functional theory calculations have been applied and found to be in good agreement with experimental data for $^{100}$Y. These data show the known sudden change in deformation at N=60.

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Electric Monopole Transition Strengths in Stable Nickel Isotopes

Electric monopole (E0) transition strengths are a useful probe for detailed investigations of nuclear structure and shape coexistence. There are surprisingly few experimentally known E0 transition strengths, especially for $J^\pi \rightarrow J^\pi$ transitions where $J>0$. The majority of known $J^\pi \rightarrow J^\pi$ cases, where $J=0$, are in the rare-earth and actinide regions where nuclei have well-deformed ground-state structures. There is a need for E0 transition strengths in closed shell nuclei in order to develop our understanding of the mechanisms responsible for the generation of electric monopole strength. In order to determine the strength of an E0 transition, a measurement of the parent lifetime, branching ratio, internal conversion coefficient and (E2/M1) mixing ratio is required. The measurement of the conversion coefficient requires simultaneous detection of gamma rays and internal conversion electrons emitted from excited states.

A series of measurements in the stable nickel isotopes were performed at the Australian National University, with the aim of establishing the physics in stable nuclei such that the physics may be reliably interpreted for exotic nuclei. Excited states in $^{58,60,62}$Ni were populated via inelastic scattering of proton beams delivered by the 14UD Pelletron accelerator. The CAESAR array of Compton-suppressed HPGe detectors was used to measure the (E2/M1) mixing ratio of multiple transitions from angular distributions of gamma rays. The Super-e spectrometer was used to measure conversion coefficients for a number of $J^\pi \rightarrow J^\pi$ transitions. New data from both devices is combined with previously measured parent lifetimes to determine E0 transition strengths.

An overview of the experiments will be presented, along with results for E0 transition strengths between $J^\pi \neq 0$ states in the semi-magic nuclei, $^{58,60,62}$Ni which provide evidence of deformed structures co-existing with the spherical ground-state configurations.

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Determining the PSF in $^{57}$Fe* with Neutron Capture

The bulk of the heavy elements (A>60) are made via neutron capture processes, whether through a rapid (r-) , slow (s-) , or intermediate (i-) process. For all of these, accurate neutron capture reaction rates are essential, particularly on unstable isotopes where direct measurements are most difficult. While the Hauser-Feshbach statistical approach can calculate reaction rates, the associated uncertainties are unacceptably large. Recent work has shown that use of the correct photon strength function (PSF) in the calculation can drastically improve the reliability of the calculation. The PSF can be measured in indirect reactions on unstable isotopes, even when the neutron capture reaction cannot be studied directly, however, some discrepancies have arisen between different probes. To address this, we have undertaken new measurements in the iron isotopes, both to resolve past discrepancies and provide a path to predictions on unstable isotopes. In this talk, I will discuss recent neutron capture measurements to populate excited states in $^{57}$Fe, the extracted PSF, and its implications for other nearby nuclei.

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Nuclear Shape Transitions and Spectroscopy of Radioactive Mo Isotopes at the CARIBU Facility

The pursuit of a ubiquitous description of transitional nuclei continues to be a central research topic in nuclear science. This is especially true as one moves into exotic regions of the nuclear landscape, where unexpected phenomena such as the migration of familiar magic numbers have been observed. Although models exist that successfully describe shell-model-like behaviour and collective motion, the actual transition from one limit to the other often remains confused.

Neutron-rich nuclei with A ~ 100 offer an exciting testing ground to develop our understanding of nuclear shape transitions. The nucleon configurations are delicate and strongly influenced by the addition or removal of only a few nucleons. Such polarisations drive the dramatic quantum phase transitions known to occur between N = 58 and N = 60 in isotopes of Sr [1] and Zr [2]. However, in Mo – despite possessing only two additional protons – the extent of deformation is less dramatic and falls well short of the rigid-rotor limit. The exceptionally low second $J^\pi = 2^+$ states may be interpreted as an indicator for triaxiality, however, the degree and ‘softness’ of the deformation are unknown.

The CARIBU Radioactive Ion-Beam facility [3] grants access to this experimentally challenging region of the nuclear landscape. Low-energy beams of $^{104, 106}$Nb fission fragments, extracted from a ~1 -Ci $^{252}$Cf source, were delivered to the X-Array, and SATURN β-decay spectroscopy station [4]. Extensive decay spectroscopy of neutron-rich $^{104, 106}$Mo was performed during the first campaign with the new hardware. This presentation will focus on the detailed expansion of the excitation level schemes, precise measurement of inter- and intra-band γ-ray transitions, and interpretation of the data within the context of nuclear shape transitions and triaxiality in the A ~ 100 region.

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Systematic Analysis of Lithium Isotope Based on Microscopic Nuclear Structure and Reaction Models

The cluster structure is one of key issues to understand the nuclear structure. The alpha cluster structure is often discussed not only in the excited state but also in the ground state. Recently, the cluster-shell competition effect has an important role to construct the ground state in the stable and unstable light nuclei [1-3]. In our study, the systematic analysis of the lithium isotope is performed and the cluster-shell competition effect is investigated for the $^8$Li nucleus from the viewpoint of the nuclear structure and reaction.

First, the 6-9Li nuclei are obtained by the stochastic multi-configuration mixing (SMCM) method [4]. The wave function of the SMCM method is fully antisymmetrized and the lithium isotope are described with the alpha, t, p and n clusters. The $^4$Li, $^7$Li and $^9$Li nuclei are described as the alpha + p + n, alpha + p + n + n and alpha + t + n + n three- or four-body systems, respectively. The $^8$Li nucleus has alpha + t + n and alpha + p + n + n + n cluster configurations. By combining two types of the cluster configuration, the cluster-shell competition in the $^8$Li nucleus is extracted. The excitation energy of the low-lying states and the radius of the ground state by the SMCM method well reproduce the data. Second, we apply the wave functions to the microscopic coupled channel (MCC) method with the complex G-matrix interaction to obtain the elastic and inelastic cross sections. The deformation effect of the ground state and the channel coupling effect are investigated on the lithium isotope elastic cross section. Furthermore, the inelastic cross section is calculated to compare the transition strength and multistep effect. We finally discuss the cluster-shell competition in the $^8$Li nucleus from the viewpoint of the nuclear structure and reaction.


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S Orbital occupancy of valence proton in $^{26-29}$P isotopes

In this work, we have found out the orbital occupancy of the valence proton in the phosphors isotopes with mass number 26 to 29 through stripping reaction mechanism. We have analyzed the longitudinal momentum distributions (LMD) of $^{25-28}$Si core fragments coming from $^9$Be($^{26-28}$P,$^{25-27}$Si)X and $^{12}$C($^{29}$P,$^{28}$Si)Y stripping reactions at high energies. The probability of occupying d-orbital by the stripped proton is found 40-60%, 30-50%, 30-50% and 0-20% in $^{26-29}$P isotopes respectively.


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**A Strong Soft Dipole Resonance in $^{11}$Li via Proton Inelastic Scattering**

Soft resonances and soft excitation of neutron halo nuclei were predicted immediately after the discovery of $^{11}$Li halo [1, 2]. However, many experimental data, including hadronic and electromagnetic reactions, so far have been controversial. Recent measurement of deuteron inelastic scattering showed a clear signal of the isoscalar dipole excitation of $^{11}$Li [3].

Here, we present a new high-resolution and high-statistics measurement of the elastic and inelastic scattering of $^{11}$Li on proton using 66 MeV incident energy at the IRIS facility at TRIUMF. The inelastic scattering data show a clear peak at an excitation energy of $0.80 \pm 0.02$ MeV with a width $\Gamma = 1.15 \pm 0.06$ MeV. The experimental resolution of the excitation energy is 170 keV (in $\sigma$) and is much smaller than the width of the observed peak.

The angular distribution of the peak was analyzed with DWBA using different transition form factors for $l=0$ to 3 transitions. For $l=0$, a breathing mode form factor, for $l=1$, Harakeh-Dieperink [4] and Orlandini form factor [5], and for $l=2,3$, the usual surface vibration mode were applied. The optimal potential for a proton interacting with $^{11}$Li was determined by the angular distribution of elastic scattering obtained simultaneously with the inelastic scattering data. The data was best fitted by an isoscalar dipole excitation. The strength of the transition was estimated to exhaust 4 to 14% of the energy-weighted sum-rule value. The observed strength is large and consistent with the simple di-neutron model of $^{11}$Li halo and also consistent with the prediction of COSM model of $^{11}$Li [6]. This agreement indicates that the present experiment confirms the soft dipole excitation of neutron halo in $^{11}$Li.

The observed peak in $^{11}$Li(p,p') spectrum is slightly lower in energy and wider than the one found in $^{11}$Li(d,d') [3]. Both experiments could be observation of the same state. However, if two or more of dipole excited states are populated through the (p,p') reaction, and those states are relatively closely spaced, then the observed peak in (p,p') could contain two unresolved dipole states. This may account for the small difference in peak position seen compared to (d,d').


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Development of the Position Sensitive Detector Using Spatial Distributions of Photons in Plastic Scintillator

In intermediate-energy nuclear physics experiments, position sensitive detectors play an important role for beam diagnostics and measurements of particle momenta. We are developing a new method for position determination of heavy ions [1]. When heavy ions pass swiftly through a scintillator, many photons are produced and emitted in an isotropic fashion. The spatial distribution of the scintillation photons correlates with the particle position on the scintillator. This principle can be applied to position-sensitive detection. A commercially available, high-sensitivity multi-anode photo multiplier tube (MAPMT) coupled with thin optical fibers realizes the sampling of photon spatial distributions.

The present detector consists of a 5-mm-thick plastic scintillator with an effective area of $100 \times 100$ mm$^2$ and 64 optical fibers with a diameter of 1 mm and a length of 200 mm. One end of each fiber is connected adjoingly in a row to the side surface of the plastic scintillator. The other end is coupled to a MAPMT. By reading out each anode signal using charge sensitive ADC, one-dimensional spatial distribution of scintillation photons is measured. Hereinafter, the present detector is called PD2 (PDSD: Photon spatial Distribution Position-sensitive Detector).

To evaluate the performance of PD2, we conducted a beam experiment at the HIMAC facility by using $^{84}$Kr beam with the energy of 200 MeV/u. We succeeded in observing the photon spatial distributions in the scintillator. In the analysis, the measured position is defined as the center of each anode channel-number weighted by ADC values. To confirm the validity of the present method, we compare the positions calculated by the PD2 and the positions of PPAC [2]. As a result, the positions by the PD2 are linearly correlated with those by PPAC. Thus, the PD2 succeeded in detecting beam positions. We measured the position resolutions by changing the bias voltage of the MAPMT. By optimizing the bias voltage and the threshold in offline analyses, we achieved the efficiency of 98% and the position resolution of 1.1 mm (1 $\sigma$).

In this contribution, we will present the details of experiment, analysis and results.

References

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Experimental Program of the Super-FRS Experimental Collaboration at the Present and Future Facilities

The Super-FRS is one of the central devices of the NUSTAR collaboration at FAIR. The separator will provide beams of exotic nuclei ranging from hydrogen to uranium over a large energy range equivalent to a maximum magnetic rigidity of 20 Tm. The exotic nuclides are produced via projectile fragmentation, fission and two-step consecutive reactions. The Super-FRS is expected to deliver exotic nuclei to the Low-Energy Branch (LEB), the High-Energy Branch (HEB) and the Storage-Ring Branch (SRB). For these dedicated experimental branches, the Super-FRS will provide spatially separated mono-isotopic or cocktail beams of rare isotopes depending on the goals of the experiments.

The detector systems placed at the different focal planes of the Super-FRS can also be used advantageously for high-resolution momentum measurements. Therefore, the Super-FRS is extremely unique also for stand-alone experiments. In addition, the energy-buncher spectrometer at the LEB can ion-optically be coupled to the main separator in a dispersion-matched mode, which yields a high momentum resolving power of 20000 for a 1mm object size.

The Super-FRS Experimental Collaboration is a sub-collaboration of NUSTAR collaboration. The presently defined scientific program of the Super-FRS collaboration is presented in a GSI report [1]. The collaboration takes advantages of the world-unique properties of the Super-FRS. Its unique properties are:

- At Super-FRS, high-energy and high-intensity primary and secondary nuclear beams can be used with energies up to 1500A MeV.
- It is a unique high-energy, high-resolution spectrometer with a large acceptance and dispersion-matching capabilities. It provides high separation power of heaviest nuclides, and also provides fully stripped ions of all elements. It provides versatile spectrometer modes by different combinations of separator sections and the placement of a target. Experimental systems for the collaboration are under developments and tested at the present FRS and at other laboratories. Also, the pilot experiments not only for testing the detectors but also for scientific researches, are in progress using the SIS/FRS and also planned as phase-0 experiments of FAIR at present facilities.

The present status of the developments and recent results of pilot experiments such as η' atoms and tensor interactions will be presented.


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Re-measurement of Transition Probability of Sn isotopes by Coulomb Excitation

Numerous experimental and theoretical studies are currently focused on nuclear shell structure far from the line of stability [1]. In particular, the evolution of basic nuclear properties, e.g., the 2+ energy of the first excited state and the reduced transition probability, i.e. B(E2; 0+→2+) value, along closed shells mark an area of great interest. The longest isotopic chain between two doubly magic nuclei are the Sn isotopes which are accessible for nuclear structure studies. Even-even nuclei along closed proton or neutron shells are often well described by the seniority scheme. (see, e.g., Ref. [2]). For the seniority scheme one expects a symmetric distribution of the B(E2) values between the two doubly magic nuclei 108Sn and 132Sn with a maximum collectivity at mid-shell (116Sn).

Recently we performed two Coulomb excitation experiments at GSI [3] and IUAC [4] to obtain high precision results for 112,114Sn isotopes. The measured B(E2) values were normalized to the one of 116Sn, which seemed to be well established [5]. Surprisingly, the experimental data showed a rather asymmetric behavior which could not be explained by shell model [6] or mean field [7] calculations.

In a recent Doppler Shift Attenuation DSA measurement [8] a reduced collectivity was found for the mid-shell Sn nuclei with up to 20% lower B(E2) values as compared to previously found data [5]. Therefore, we performed a series of Coulomb excitation experiments at IUAC in order to excite all stable Sn isotopes (112,116,118,120,122,124Sn) with a 58Ni beam. Both projectile and target nucleus were excited and from the 2+ intensities the B(E2) value ratios can be determined in a straight forward manner. Based on our measurements we cannot support the reported reduced collectivity [8]. We will report on the details of our Coulomb excitation experiments and will compare our experimental results with theoretical predictions.

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First Mass Measurement Using Rare-RI Ring

The Rare-RI Ring is an isochronous storage ring to measure masses of short-lived rare nuclei by using Time of Flight (TOF) measurement method [1,2]. Two demonstration of mass measurement using Rare-RI Ring have been performed. In the first demonstration, masses of $^{35}\text{Cl}$ and $^{36}\text{Ar}$ have been measured and the second demonstration, masses of well-known nuclei $^{79}\text{As}$, $^{77,79}\text{Ge}$, $^{76}\text{Ga}$, $^{76}\text{Zn}$, and $^{75}\text{Cu}$ have been measured. We injected these nuclei to the ring using the individual injection with the fast kicker system [3]. In the second demonstration, the isochronous magnetic field of the ring was adjusted for reference particle of $^{79}\text{Ge}$. We confirmed the storage of particles by using an in-ring detector. We also successfully extracted these nuclei from the ring. The isochronous condition for the particles of interest is slightly different. To evaluate the masses of nuclei with non-isochronism, we correct the TOF in the ring by the velocity measured at upstream of the ring. Using their TOF in the ring and velocity, we deduced their masses. In this contribution, the results of the demonstrations of mass measurement will be discussed.

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Energy dependence of Glauber model and determination of proton distribution of neutron-rich carbon isotopes from charge-changing cross section measurement at 45 $A$ MeV

The root-mean-square (rms) radius of point proton distribution in a nucleus (referred to as "proton radius" hereinafter), together with matter radius, of a nucleus is one of the most important observables. The electron scattering is the most successful method to investigate the charge distribution of nuclei and thus the proton distribution, but it has mostly been applied to stable nuclei. For unstable nuclei, the isotope shift technique has been the most important method. However, this technique also becomes challenging for nuclei with $4<Z<11$ due to the uncertainty in the atomic physics calculation. The recent progress of Glauber model analysis has enabled the extraction of matter radii from interaction ($\sigma_I$) and/or reaction ($\sigma_R$) cross section at relativistic energy [1]. This Glauber-type calculation has been extended and applied to extract the proton radii from the charge-changing cross section ($\sigma_{CC}$) measurements at high energy for Be, B, C isotopes. The results were shown to be consistent with the electron scattering and isotope shift methods, thus suggesting the possibility to determine proton radii from the $\sigma_{CC}$'s using the Glauber model. Studying energy dependence of the cross section enables to determine not only the rms radii but possibly also the shape of density distribution [6]. We have measured, for the first time, the $\sigma_{CC}$'s of $^{12-18}$C on a $^{12}$C target at energies below 100$A$ MeV. To analyze these low-energy data, we have developed a finite-range Glauber model with a global parameter set within the optical-limit approximation [2], which is applicable to $\sigma_R$'s and $\sigma_{CC}$'s at incident energies from 10$A$ to 2100$A$ MeV. Applying the Glauber calculation to our measured $\sigma_{CC}$'s, the proton radii for $^{12-18}$C have been extracted. The consistency of obtained results with the electron scattering and high energy [3] measurements demonstrates the feasibility to determine the proton radii of nuclei from $\sigma_{CC}$ measurement at low energy. Using energy dependence of the $\sigma_{CC}$'s, we have evaluated the model-density- distribution dependence of the neutron and proton radii for $^{13-15}$C. The results suggest the importance of the $\sigma_{CC}$ and $\sigma_{CC}$ measurements at low energy. In this talk, the results of experiment as well as the Glauber analysis will be discussed.


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Interplay of Collective and Single-particle Regimes in Os-168

Dramatic structural changes have been observed in very neutron-deficient Os nuclei when approaching the N=82 shell closure in terms of the B(E2) values. Near the neutron mid shell, the nuclei exhibit rotational prolate characteristics in their level energies. Beyond that the collectivity decreases with decreasing neutron number and the shape coexistence sets in at Os-172. When approaching the shell closure at N=82, the shape of the nuclei is expected to become spherical and indeed such development is observed.

The nucleus Os-168, which lies between the rotational and vibrational regimes, has been studied in detail at the Accelerator laboratory of the University of Jyväskylä. In particular, mean lifetimes of excited states have been measured with the recoil distance Doppler-shift method following a heavy-ion induced fusion-evaporation reaction and by utilizing selective tagging methods. The gamma-rays have been recorded with the JUROGAM gamma-ray spectrometer that is combined with the RITU recoil separator. The Köln plunger device was installed at the target position of JUROGAM. The transition probabilities between the low-spin states in Os-168 exhibit an unusual phenomenon, in which the observed ratio of the B(E2) values from the 4+ and 2+ states (B_{4/2}=0.34(18) \[1\]) differs considerably from any theoretical model.

The results will be discussed within different theory frameworks and compared with the typical nuclear structure derived for the nuclei in this region of the nuclear chart. In addition, similar features in the vicinity of Os-168 will be discussed.


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The Super-FRS GEM-TPC Tracking Detector

The Super-FRS fragment separator in construction at FAIR will be a core device for the physics programme of the NUSTAR collaboration. Majority of the experiments will require clean identification of rare isotopes produced in in-flight fragmentation and fission. Therefore, the GEM-TPC detector has been developed for tracking of the fragments produced at Super-FRS. The detector concept combines two widely used approaches in gas-filled detectors, the Time Projection Chamber (TPC) and the Gas Electron Multiplication (GEM). Due to the high-resolution achromatic mode of Super-FRS, highly homogeneous transmission tracking detectors are crucial to tag the momentum of the fragments. They must be able to provide precise information on the (horizontal and vertical) deviation from the nominal beam optics, while operated with slow-extracted beam on the event-by-event basis, in order to contribute to the unambiguous identification of the fragments, together with the energy loss and time-of-flight measurements. Moreover, the experiments proposed by the Super-FRS Experiment Collaboration of NUSTAR will use Super-FRS in the separator-spectrometer mode, in which the tracking detectors will be used to record data for experiments. The design and beam test results of the GEM-TPC detector will be presented.

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Isobaric Multiplet Mass Equation within Density Functional Theory

The isospin-symmetry breaking (ISB) due to the strong nuclear force manifests itself not only in nucleon-nucleon scattering experiments and structure of light nuclei [1], but also in binding energies of heavier systems [2]. Isobaric Multiplet Mass Equation (IMME) is a systematic approach to describe the influence of charge symmetry and charge independence breaking (introduced both by Coulomb force and the strong interaction). Together with precise mass measurements it provides valuable information and a strict test of ISB in atomic nuclei. In our latest study [3] we have extended the conventionally-used isospin-invariant Skyrme energy density functional by adding novel zero-range ISB terms of class II and class III (according to the classification proposed by Henley and Miller [4]). The two new coupling constants were fitted to all available data on Mirror and Triplet Displacement Energies (MDE, TDE) in a broad range of masses (A=10-75). The extended model was able to reproduce the experimental values of MDE in both T=1/2 and T=1 multiplets and, for the first time, values of TDE in T=1 triplets including their characteristic staggering pattern.

In the first part of my presentation, I will briefly overview the formalism and main results of Ref. [3]. Next, I will demonstrate that the IMME coefficients calculated with our model can be used to reliably predict binding energies of neutron-deficient nuclei including masses of recently measured heavy N-Z systems, see Refs. [5,6]. Eventually, I will concentrate on isobaric triplets in light nuclei aiming to bridge our effective charge-dependent (CD) forces with fundamental CD interactions. This will be achieved by decomposing the IMME coefficients into contributions due to charge-independent, CD electromagnetic, and CD strong components in the functional and subsequent comparison of the DFT results to the available ab initio calculations [7,8].


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Towards On-Line High-resolution In-source Laser Spectroscopy: A Perpendicular Laser - Atom Beam Upgrade for the Laser Ion Source and Trap LIST

Highly selective and efficient laser ion sources are of fundamental importance to study atomic and nuclear properties along the nuclear chart. Upgrading the well-established, highly element-selective laser resonance ionization technique with additional suppression of isobaric contaminations immediately at the exit of the hot ion source cavity led to the development of the Laser Ion Source and Trap LIST. In the recent years, it was successfully operated at ISOLDE e.g. for investigations on neutron-rich polonium isotopes, which were previously experimentally inaccessible due to the overwhelming fraction of surface ionized francium [1, 2].

For highest precision in spectroscopic studies and isomer-selective ionization and ion beam production, a perpendicular laser - atom beam interaction geometry has been integrated into the LIST’s RFQ ion guide structure. This reduces the experimentally realized spectral linewidth, which is dominated by the Doppler broadening in the hot atom vapor, from a few GHz down to below 100 MHz. Off-line hyperfine structure investigations on long-lived radioactive $^{97,99}$Tc isotopes, using frequency-doubled narrow bandwidth radiation of an injection-locked high repetition rate titanium:sapphire laser [3], demonstrate the potential of this development [4]. An additional repelling electrode inhibits electron impact induced ionization mechanism in the laser - atom interaction region, ensuring lowest background rates and efficient measurements on minuscule samples of $10^{11}$ atoms, with perspective to even lower amounts. In the framework of the ECHO project [5], high resolution hyperfine structure studies were performed on the radioisotopes $^{163,166m}$Ho at the ISOLDE-like RISIKO off-line mass separator at Mainz University, featuring a potentially on-line suitable adaption of the perpendicular laser beam guidance based on robust metal mirrors inside the ion source unit.

Results and measurement methods are presented, and opportunities and constraints of this novel PI-LIST (Perpendicularly Illuminated) design are derived.

References

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Poster ID : 139

**Low-energy Resonances in $^{12}$C**

Stars and supernovae are the factories of the universe and all but the three lightest elements are produced here. The $^{12}$C nucleus is one of the first links in the production chain of the heavier elements, which explains why many astrophysicists take a particular interest in the exploration and study of the structure of this nucleus. In the talk some results from a recent beta decay experiment at IGISOL in Jyväskylä are presented. The beta decay of $^{12}$N populates $^{12}$C in both its ground state and several of its excited states. If the populated state has an excitation energy above the alpha emission threshold, there is a large probability that the $^{12}$C system breaks apart and emits three low-energy alpha particles. A sequential decay model is combined with the well-established R-matrix formalism, and with the help of Monte Carlo simulations the theoretical model is compared to the experimentally observed three-particle states. It is concluded that the excitation spectrum of $^{12}$C is dominated by $0^+$ strength at excitation energies in the 8MeV-12MeV range, while in the 12MeV-15MeV region there are competing $0^+$ and $2^+$ contributions.

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**Precision Measurements of Mirror Transitions at the University of Notre Dame**

The Standard Model (SM) as a description of matter in the universe contains many unexplained features. One way to search for physics beyond the SM is accomplished by testing the unitarity of the Cabibbo-Kobayashi-Maskawa matrix. Such a unitarity test requires a precise and accurate determination of the $V_{ud}$ matrix element, which is currently achieved via the precise determination of the $f^T$-value of electroweak decays. While superallowed pure Fermi transitions currently allow for the most precise determination of $V_{ud}$, there is currently a growing interest in obtaining that matrix element from superallowed mixed transitions to test the accuracy of $V_{ud}$ and the calculation of the isospin symmetry breaking correction. In the past year a research program aimed at solidifying the determination of $V_{ud}$ from mirror transitions was initiated using radioactive ion beams from the Twin Solenoid (TwinSol) separator at the NSL. The first part of the program is centered on precision lifetime measurements and the second part aims at measuring the Fermi to Gamow-Teller mixing ratio $\rho$. Recent half-life measurements and our plan for building an ion trapping system to measure $\rho$ in many mirror decays for the first time will be presented.

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Spectroscopy of Neutron-rich $^{69,71,73}$Co Isotopes

$^{68}$Ni ($Z = 28, N = 40$) can be considered as doubly magic nuclei due to the level structure of first and second excited states [1], and while it can described as spherical isotope, $^{66}$Fe ($Z = 26, N = 40$) is well deformed one [2]. Co isotopes are in between Ni and Fe nuclei and found to share coexistence of both spherical and deformed structures in low-lying excited states [3], which can be described as interposition between a proton $f_{7/2}$ hole coupled to neighboring spherical even- even nickel isotopes and a proton intruder to well deformed Fe nuclei [4]. Therefore it is very interesting to measure spectroscopy of $^{69,71,73}$Co isotopes to study the shape evolution towards south-east from $^{68}$Ni and shell transformation from $N = 40$ to $N = 50$.

In-beam gamma experiment was performed at RIKEN to study Co isotopes. Secondary beam of Ni isotopes at energy of 260 MeV/u bombarded liquid hydrogen target (MINOS [5, 6]) to produce $^{69,71,73}$Co via (p, 2p) reaction. Excited states of nuclei were studied using DALI2 gamma-ray detector array [7]. Level schemes of $^{69,71,73}$Co were investigated via gamma-gamma coincidence technique. To shed the light on the development of deformation of nuclei measured states of $^{69,71,73}$Co were compared to the systematic behavior with lighter Co isotopes and corresponding Ni and Fe isotopes. In this poster session, the experimental setup and the physics results will be discussed. References.

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Study of Static Quadrupole Moments in $^{120}$Te Isotope

In recent years, the region in the vicinity of tin isotopes has been intensively investigated both from experimental and theoretical perspectives. In particular, the excitation energies and the reduced transition probabilities across the Z=50 chain have been examined in detail. The Te nuclei with Z=52 lie in the transitional region between the spherical nuclei at Z=50 and deformed Xe and Ba nuclei. For the mid-shell $^{120,122,124}$Te nuclei, the partial level schemes show the expected vibrational-like structure with equal energy spacing between the phonon states [1]. This observation is quite in contrast to the measured quadrupole moments Q(2+) for the doubly even Te isotopes [2, 3]. These quadrupole moments can reach 60% of the one predicted by the symmetric rigid rotor.

In our recent Coulomb excitation experiment [4] at IUAC, New Delhi, we used $^{58}$Ni beam @ 175MeV to excite $^{120,122,124}$Te isotopes. In these measurements, the scattered particles were detected at forward angles. The B(E2; 0→ 2+) value in $^{120}$Te was re-measured with a much higher precision to allow a comparison with the predictions of the large scale shell model calculations (LSSM). Based on all experimental findings including the excitation of higher excited states for $^{120,122,124}$Te, one obtains the best agreement with an asymmetric rotor behavior. Calculations were performed using the Davydov-Filippov model which reproduce the reduced transition probabilities with β=0.19 and γ~30°. But, microscopic calculation (using the Skryme effective interaction) performed point towards a vibrational structure with a mean value of γ~30°. The most sensitive probe to characterize a nuclear excitation is via the measurement of quadrupole moments.

Therefore, to further investigate the second order effects (diagonal matrix elements) in $^{120}$Te, an experiment was performed at Heavy Ion Laboratory, Warsaw, where particle detectors are in the backward direction enabling a more precise and sensitive measurement of the quadrupole moments. The measurement was carried out using a highly enriched $^{120}$Te target and a $^{32}$S beam @ 100 MeV from the U-200P cyclotron at HIL. A multi-step Coulomb excitation of $^{120}$Te was observed up to 4+ state in the g.s. band. The results will be presented at the conference.

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Measurements of Isomer Properties at the FRS Ion Catcher

The interest in isomers ranges from nuclear structure and astrophysics to their possible use for energy storage devices or medical applications. The relative population of isomer and ground states and excitation energies of short-lived exotic nuclei have been determined at the FRS Ion Catcher at GSI. At the FRS, nuclear isomers were produced in projectile fragmentation and fission reactions at relativistic energies, separated in-flight and energy-focused. They were slowed down and thermalized in a cryogenic stopping cell. The ions were transported to a multiple-reflection time-of-flight mass spectrometer (MR-TOF-MS), where masses of the ground and isomeric states can be measured simultaneously. This method gives access to isomers with a half-life longer than 1 ms and is thus fully complementary to gamma-ray spectroscopy. The MR-TOF-MS can also be used to spatially separate pure isomeric ion beams [1]. This has opened new possibilities towards mass-selective decay spectroscopy.

For the first time, an isomerically clean beam has been separated with an MR-TOF-MS as demonstrated with $^{211}$Po ions. Results of isomeric-to-ground state ratios and excitation energies of uranium and xenon projectile fragments and uranium fission products measured with the MR-TOF-MS will be presented. In total about 15 isomers were measured with a mass resolving power up to 450,000. Systematic investigation on the relative population of isomer and ground states and excitation energies were done with proton-rich indium isotopes.

The measured isomeric-to-ground state ratio reflects the angular momentum distribution after fragmentation or fission reactions and provides new information towards their production mechanisms. The isomeric-to-ground state ratios measured with the MR-TOF-MS are compared to calculations based on an abrasion-ablation model of fragmentation.

References:
Triaxiality and Collectivity in $^{78,80}$Ge

The stable even Ge isotopes have been of much interest for quite some time as the observed level structures are indicative of shape coexistence and triaxiality. The present work aims at expanding our understanding further by providing new information on the neutron-rich $^{78,80}$Ge isotopes. The level schemes of these two isotopes have been considerably expanded based on data obtained with Gammasphere at the ATLAS facility using multi-nucleon transfer reactions with a $^{76}$Ge beam on several high-Z targets. The level structure of $^{80}$Ge below 4 MeV is found to be fully consistent with that predicted by the shell model, with the exception of a new 0+ intruder state at 639 keV [1]. In $^{78}$Ge, the known yrast sequence [2] has been extended toward higher spins, a new sequence of presumed dipole transitions connecting positive-parity levels, several negative-parity states, and seniority-4 levels have been established as well. The implications of the results for the onset of deformation, triaxiality, and collectivity as the neutron number is reduced below the N=50 closed shell will be discussed.

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Simulating the DESCANT Neutron Detection Array with the Geant4 Toolkit

The DEuterated SCintillator Array for Neutron Tagging (DESCANT) is a newly developed high-efficiency neutron detection array composed of 70 hexagonal deuterated scintillators. Due to the anisotropic nature of elastic neutron-deuteron (n,d) scattering, the pulse-height spectra of a deuterated scintillator contains a forward-peaked structure that can be used to determine the energy of the incident neutron without traditional time-of-flight methods. Simulations of the array are crucial in order to interpret the DESCANT pulse heights, determine the efficiencies of the array, and examine its capabilities for conducting various nuclear decay experiments. To achieve this, we plan: (i) a verification of the low-energy hadronic physics packages in Geant4, (ii) a comparison of simulated spectra with data from a simple cylindrical "test can" detector geometry, (iii) expanding the simulated light response to a prototype DESCANT detector, and (iv) simulating the entire DESCANT array.

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A Study on Low Spin States in $^{154}$Gd Using (p,p') Reaction

The investigation of N = 90 nuclei have been the subject of many experimental studies. These isotones, such as $^{154}$Gd and $^{152}$Sm, lie at the center of a region of rapid shape change between vibrational and rotational characteristics, and demonstrate striking similarities. The low lying spin states of the $^{154}$Gd nucleus were investigated at the University of Jyvaskyla accelerator laboratory in Finland, using the $^{154}$Gd(p,p'$\gamma$) reaction. A proton beam of 12 MeV was used to excite the $^{154}$Gd target, with the $\gamma$-rays from the reaction detected with the JUROGAM II array, while the LISA charged-particle spectrometer was used for detection of the inelastically scattered protons. This experiment marked one of the first uses of the LISA spectrometer at Jyvaskyla, which enabled the efficient tagging of the proton-emitting reactions, thus helping to distinguish between the (p,p') and the much more copious (p,xn) channels. By analysing the peaks obtained from the gamma-gamma, and gamma-gamma-proton coincidence matrices, a decay scheme has been built using the RadWare software Escl8r. Experimental methods, new transitions, gamma branching ratios, and future steps will be discussed.

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From CERN ISOLDE to CERN MEDICIS: novel radioisotopes for medical applications

The production of medical radioisotopes is largely dominated by neutron capture at nuclear reactors and fusion-evaporation reactions with cyclotrons based at medical facilities. While those techniques are quite efficient, only a handful of different radioisotopes are regularly used by the medical community. This is in part due to the difficult access to novel radioisotopes during the long pre-clinical and clinical studies.

In contrast to this picture, the ISOL technique is rather inefficient for a given radioisotope, but it provides access to a wide catalog of radioisotopes for research. This has motivated a research programme at CERN ISOLDE that has successfully supported the study of, e.g., the theranostic set of Tb isotopes [1]. In order to further support the research emerging from these successes and to ensure a reliable access for medical research teams, a new facility dedicated to the production of radioisotopes by the isotope mass separation method is currently under commissioning at CERN.

CERN MEDICIS (MEDical Isotopes Collected from ISolde) [2] consists in a parasitic irradiation point where target units can be activated at ISOLDE, a rail system that can remove those targets from the high-radiation area to an offline separator facility where the ISOLDE know-how can be applied to extract the radioisotopes of interest. Partnership with regional, European and international collaborators allows a community to exchange on these novel radioisotopes from their production up to their use in pre-clinical research.

In this contribution, we shall report on some recent highlights from the medical radioisotope programme at ISOLDE and on the progress of the installation and commissioning of the CERN MEDICIS facility. Part of these activities are developed in the framework of MEDICIS-Promed, a Marie Skłodowska-Curie Innovative Training Network training 15 PhD students [3].


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Status of CHIP-TRAP: The Central Michigan University High-Precision Penning Trap

Ultra-high precision atomic mass determinations, to fractional precisions of ~0.1 – 0.01 ppb or better, are required for a number of different applications. In some cases, ultra-high precision mass measurements with long-lived radioactive isotopes are called for. For example, a measurement of the $^{36}\text{Cl} - ^{35}\text{Cl}$ mass difference will provide the $^{36}\text{Cl}$ neutron binding energy, which can be compared with a high-precision gamma-ray spectroscopy determination for a direct test of $E = mc^2$. Measurements of the $^{163}\text{Ho} - ^{163}\text{Dy}$ and $^{187}\text{Re} - ^{187}\text{Os}$ mass differences will provide the $^{163}\text{Ho}$ electron capture and $^{187}\text{Re}$ beta-decay Q-values, respectively. These independent Q-value determinations are required for experiments that aim to determine the neutrino mass via electron capture spectroscopy of $^{163}\text{Ho}$ or beta decay spectroscopy of $^{187}\text{Re}$.

At Central Michigan University we are developing a high-precision Penning trap (CHIP-TRAP) for precise mass measurements with stable and long-lived isotopes. CHIP-TRAP will consist of a pair of hyperbolic precision measurement traps and a cylindrical capture/filter trap located in a 12 T magnetic field. Ions will be produced using a laser ablation ion source (LAS) and transported to the capture trap at low-energy using electrostatic ion optics. In the capture trap ions will be identified via Fourier Transform Ion Cyclotron Resonance (FT-ICR) techniques, and unwanted ions will be removed using mass-selective rf dipole excitation. The ion of interest will then be moved to one of the precision measurement traps. The goal of this project is to simultaneously measure the cyclotron frequency of two ion species, each confined in one of the precision measurement traps. This will result in a cancellation of magnetic field fluctuations to lowest order and an associated reduction in statistical uncertainty. The cyclotron frequency measurements will be performed using a phase sensitive image charge detection technique with single ions.

In this presentation we will report on the design, construction, and testing of the LAS and on the overall status of the CHIP-TRAP project.

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Low-Energy Coulomb Excitation with SeGA/JANUS

With the existing ReA3 reaccelerator facility at the NSCL and the beams that will be available from FRIB in the future, a wide variety of low-energy exotic beams will be usable for nuclear structure experiments. The SeGA/JANUS experimental setup is designed to take advantage of these beams. SeGA [1], the Segmented Germanium Array, is an existing gamma-ray detector array that has been enhanced with digital data acquisition and pulse-shape analysis. Combined with JANUS, which consists of two annular silicon detectors, the setup is ideal for sub-barrier Coulomb excitation, which can probe transition strengths and moments beyond the first excited state. The setup has been commissioned with a measurement of $^{78}\text{Kr}$, and preliminary results will be presented.

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The enhancement of alpha-particle preformation for the nuclei above 100Sn is expected due to the occupation of the same orbitals by valence neutrons and protons outside the N=Z=50 shell closure [1]. The search for new alpha-emitters in this region was carried out at the Japan Atomic Energy Agency tandem accelerator facility at Tokai, Japan. This work aimed to discover $^{113}$Ba produced via fusion-evaporation reaction and observe its alpha-decay chain $^{113}$Ba $\rightarrow$ $^{109}$Xe $\rightarrow$ $^{105}$Te $\rightarrow$ $^{101}$Sn. In the proof-of-principle experiment, the alpha-decay chain of 109Xe was detected using a Double-sided Silicon Strip Detector (DSSD) and digital electronics at JAEA Recoil Mass Separator (RMS) [2]. The first $^{113}$Ba experiment was carried out in December 2014 and several candidates for decay of this isotope were observed. The latest result of analysis will be presented.

References:
Towards Laser Spectroscopy of Boron-8

The BOR8 experiment aims at the determination of the nuclear charge radius of boron-8 with high-resolution laser spectroscopy. $^8$B is perhaps the best candidate of a nucleus exhibiting an extended proton wave-function or one-proton-halo. Strongest evidence for the halo character of the proton comes from the unusually large quadrupole moment of this proton-rich nucleus as measured by β-NMR [1]. The most decisive observable, the nuclear charge radius, which is directly correlated with the extent of the proton wave function, can be extracted in a model-independent way from the measured isotope shift along the boron isotopic chain. Atomic theory calculations of the five-electron system, which were recently carried out [2], pave the way for targeting neutral boron atoms, whose spectroscopic properties are well suited for such measurements.

$^8$B is produced in-flight via the $^6$Li($^3$He,n)$^8$B reaction in a liquid-nitrogen cooled $^3$He gas target, and subsequently thermalized in a Helium gas catcher system. This technique is already employed for electro-weak studies of the $^8$B beta-decay [3] at Argonne National Laboratory (ANL), where the primary $^6$Li beam at 45 MeV is provided by the Argonne Tandem Linac Accelerator System (ATLAS).

We will employ a collinear laser spectroscopy technique to measure the isotope shifts. The secondary low-energy (~10 keV) $^8$B beam extracted from the gas catcher will be overlapped with two laser beams set up in co- and counter propagating direction. This allows to correct for the large Doppler shifts inherent in the collinear technique and to extract the boron isotope shift with the required precision. A similar approach was utilized for the successful measurement of the charge radii in the Be isotopic chain up to $^{12}$Be at CERN-ISOLDE [4].

In a first off-line experiment at TU Darmstadt, the isotope shift of the stable isotopes $^{10,11}$B has been measured with resonance ionization mass spectrometry. This provides a valuable test not only of atomic theory, but also of experimental equipment which will later be used at ANL.

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References:

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High Precision Mass Measurements of Exotic Nuclei with a Multiple-Reflection Time-of-Flight Mass Spectrometer

A multiple-reflection time-of-flight mass spectrometer (MR-TOF-MS) [1] for the research with exotic nuclei at GSI Darmstadt has been developed. The device is used to perform highly accurate mass measurements of exotic nuclei, to serve as high-resolution, high-capacity mass separator and to be employed as diagnostics device to monitor the production, separation and manipulation of exotic nuclei beams [2]. The MR-TOF-MS is a non-scanning mass spectrometer capable of measuring singly and doubly charged ions at the same time.

During the recent experiments in 2014 and 2016, exotic nuclei were produced via projectile fragmentation and fission of $^{238}\text{U}$ and $^{124}\text{Xe}$. A total of more than 40 masses of nuclei with half-lives down to tens of milliseconds were measured with mass resolving powers up to 450,000 FWHM. Of these isotopes, seven were directly measured for the first time. A method for the evaluation of the data which is able to cope with overlapping peaks (isomers) and very low statistics (<10 detected ions) has been developed. This allows us to evaluate the mass of exotic isotopes with production cross sections in the microbarn range. A systematic investigation of the uncertainties of the MR-TOF-MS has been performed. A mean systematic uncertainty of 0.3 ppm has been obtained.

An overview on the mass measurements performed with the MR-TOF-MS at the FRS Ion Catcher during the recent experiments will be presented.

References:
Development of an Actinide Ion Source by In-gas-cell Laser Resonance Ionization at the IGISOL Facility

High resolution optical spectroscopy for measuring nuclear ground and isomeric state properties has thus far been limited in the heavy actinide element region. Therefore, a program of research towards obtaining such information is currently ongoing at the IGISOL facility of the University of Jyväskylä. Access to actinide nuclei can be realized through laser ionization of bulk (ng) samples of material produced in nuclear reactors. Via this method the first measurement of several long-lived isotopes of plutonium has been performed at the collinear laser spectroscopy facility [1,2] and in the near future, measurements on thorium isotopes will commence, including thorium-229, related to the search for the elusive low-energy isomeric state.

In order to provide ion beams of actinide elements, a new gas cell has been constructed taking into account the high purity and fast extraction requirements for in-gas-cell laser ionization. Resonance laser ionization has been successfully performed on isotopes of plutonium [3] and thorium evaporated from tantalum filaments via electro-thermal heating inside the gas cell. Characterization of the gas cell has been done by studying the chemical and dynamic processes. Preliminary tests using a uranium-233 alpha recoil source in helium to produce a beam of thorium-229 ions in the isomeric state has also been done. In addition, further investigation of the plutonium laser ionization scheme has recently been done in collaboration with the Applied Quantum Beam Engineering group from Nagoya University using their tunable, grating-based, Ti:sapphire laser. In this presentation the characterization of the gas cell as well as the laser ionization studies of both elements will be presented.

References:

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Searching for Cluster States in Isospin Mirror Nuclei C-14 and O-14 Using Radioactive Beams at TwinSol

A variety of cluster configurations have been proposed for the neutron-rich C isotopes from a number of cluster models including molecular orbital models and anti-symmetrized molecular dynamics. In particular, several groups have studied resonances above the Be-10 + alpha threshold and have proposed candidates for strongly clustered states in C-14. It remains to be seen if similar structures can be found on the proton-rich side of stability and the search for the isobaric analogs to these proposed cluster states would shed light on both the question of the existence of cluster states on the proton-rich side of stability and whether strong cluster states exist in C-14.

We have performed a C-10 + alpha scattering experiment to search for such states above the alpha threshold to probe resonances in O-14. A beam of C-10 produced using TwinSol at the University of Notre Dame and the Prototype Active-Target Time-Projection Chamber were used for the measurement of excitation functions and angular distributions for a range of energies above the alpha threshold. The current status of the analysis of this experiment will be presented including advances in obtaining tracking information from the active target data as well as future plans for supplemental measurements.

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FRS Ion Catcher: Precision Experiments with Thermalized Projectile and Fission Fragments

The FRS Ion Catcher experiment at GSI enables precision experiments with projectile and fission fragments. The fragments are produced at relativistic energies in the target at the entrance of the fragment separator FRS, spatially separated and energy-bunched in the FRS, slowed-down and thermalized in a cryogenic stopping cell (CSC). A versatile RFQ beamline and diagnostics unit and a high-performance multiple-reflection time-of-flight mass spectrometer (MR-TOF-MS) enable a variety of experiments, including high-precision mass measurements, isomer measurements and mass-selected decay spectroscopy. At the same time the FRS Ion Catcher serves as test facility for the Low-Energy Branch of the Super-FRS at FAIR.

In five experiments with 238-U and 124-Xe projectile and fission fragments produced at energies in the range from 300 to 1000 MeV/u the performance of the CSC has been characterized. The stopping and extraction efficiencies, the extraction times and the rate capability have been determined, and the charge states and the purity of the extracted ions have been investigated. Based on these studies, a novel concept for the CSC for the LEB has been developed. High-accuracy mass measurements of more than 40 projectile and fission fragments have been performed at mass resolving powers up to 450,000 with production cross-sections down to the microbarn-level and at rates down to a few ions per hour. The masses of 7 nuclides have been measured directly for the first time, including 220-Ra, 213-Rn and 217-At with half-lives of 17.5 ms, 19.5 ms and 32.3 ms, respectively. A novel data analysis method for MR-TOF-MS measurements on rare nuclides has been developed, and a mean systematic uncertainty of 0.3 ppm has been obtained. Access to millisecond nuclides has been demonstrated by the first direct mass measurement and mass-selected half-life measurement of 215-Po (half-life 1.78 ms). The versatility of the MR-TOF-MS for isomer research has been demonstrated by the measurements of 15 isomers, determination of excitation energies and the production of an isomeric beam. The isotope-dependence of proton-rich indium isotopes has been measured. The determination of isomeric ratios gives access to the study of the mechanisms of projectile fragmentation and fission. Furthermore, the novel method of range-selection of relativistic fragments enables alpha spectroscopy of pure samples.

References:

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Poster ID : 180

**Developing Nucleon Self-energies to Generate the Ingredients for the Description of Nuclear Reactions**

Various aspects and applications of the non-local implementation of the dispersive optical model (DOM) are reported. The analysis of the $^{40}$Ca(e,e'p)$^{39}$K reaction has been revisited, which requires both bound and continuum states to calculate its cross section. The real and imaginary potentials of the DOM are constrained by fitting to elastic-scattering data, total and reaction cross sections, energy level information, and the charge density of $^{40}$Ca. The experimental analysis of the $^{40}$Ca(e,e'p)$^{39}$K employed local non-dispersive potentials in a distorted-wave impulse approximation (DWIA), providing the accepted values of 0.65 and 0.5 for the spectroscopic factors of the $0d_{3/2}$ and $1s_{1/2}$ orbitals, respectively. The DOM generates 0.76 and 0.74 for these spectroscopic factors, respectively. The cross sections calculated with DOM ingredients are described as well as in the original analysis, demonstrating that a proper description of the (e,e'p) reaction is indeed obtained through the DWIA for sufficiently high energies of the detected proton.

The combined DOM analysis of $^{40}$Ca and $^{48}$Ca generates a neutron skin of 0.245 with a 10% error, which is substantially larger than a recent ab-initio calculation. This DOM analysis is currently extended to $^{208}$Pb with the goal of generating its neutron skin. A relativistic extension of the DOM is also being investigated. The effects of the underlying nucleon-nucleon tensor force is investigated by explicitly including the Hartree-Fock contribution of the self-energy for various nucleon-nucleon interactions.

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Poster ID : 183

**Neutron-Proton Equilibration Chronometry in Dynamically Deformed Nuclear Systems**

Understanding the neutron-proton (NZ) equilibration dynamics may lead to constraints on the asymmetry energy component of the nuclear equation of state (nEoS). The extent of equilibration is governed by the contact time and the gradient of the potential driving the equilibration. We have studied the correlations between the three largest fragments of the excited projectile-like fragment (PLF*) produced in collisions of $^{70}$Zn + $^{70}$Zn at 35 MeV per nucleon measured with the NIMROD detector at the Cyclotron Institute at Texas A&M University. Measuring the composition of the fragments as a function of the rotation angle allows direct observation of the time dependence of NZ equilibration. This technique enables new insight into the density dependence of the asymmetry energy which is the largest uncertainty in the nEoS.

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Low-lying Band Structure of $^{98}$Zr

The rapid onset of deformation across the Zr (Z=40) isotopes is unprecedented in the nuclear chart and, despite the great effort (both experimental and theoretical) dedicated to understanding it over the last decades, only recently are we gaining some insight on how this phenomenon occurs. This rapid increase of deformation has been interpreted as type II shell evolution, with a quantum phase transition occurring as the number of neutrons increases [1]. The critical point occurs in the transition from N=58 to N=60, where the 2$^+$ state drops abruptly in energy by a factor of six. In this scenario, $^{98}_{40}$Zr$_{58}$ is a key nucleus to understand the evolution of this sudden change from a spherical to a strongly deformed ground state just by the addition of two neutrons. Despite its importance, the structure of this nucleus is far from clear, with the most recent experimental results in disagreement over the key branching ratios that determine its band structure at low energies [2,3].

To elucidate the lower-lying band structure of $^{98}$Zr a high-statistics $\gamma\gamma$, $\gamma$-e$^-$ experiment was performed. This experiment was aimed at precisely measuring very weak low-energy branching ratios in the decay scheme, which due to the energy dependence of the quadrupole transitions ($E_2^\gamma$ for E2 transitions), is dominated by high-energy $\gamma$-transitions. This effect may obscure low-energy lines, even those with a large reduced transition rate, resulting in a failure to identify band structures.

The experiment was carried out using the 8$\pi$ spectrometer at TRIUMF-ISAC, which consists of an array of 20 Compton-suppressed high-purity germanium detectors in conjunction with 5 high-energy-resolution Si(Li) for conversion electrons. Excited states up to ~5 MeV in $^{98}$Zr were populated in the $\beta^-$ decay of $^{98}$Y $J^\pi=0^-$, greatly expanding the known level scheme.

A new interpretation of the $^{98}$Zr nuclear structure based on triple shape coexistence will be presented. These results are in agreement with the type II shell evolution interpretation and show strong similarities between the nuclear structure of $^{98}$Zr and the semi-magic nucleus $^{68}$Ni.

References:

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**Web Development of Nuclear Density Function Theory**

In an effort to share the results of our large scale nuclear DFT calculations, the website MassExplorer has been created. It contains mass table calculations of various ground state nuclear properties (such as binding energies, charge radii etc.) of even-even nuclei, approximations of binding energies of even-odd and odd-odd systems, and single quasiparticle states for magic and doubly magic nuclei. To learn more about the systematic errors of our calculations, mass tables for six different EDFs are shown.

The salient feature of MassExplorer is its graphical interface. This includes the capacity to generate plots of our mass table results for isotopic, isotonic, and isobaric chains, allowing the user to have immediate access to visual trends and patterns; plots of multiple chains to visualize correlations are also available. The interface also contains two-nucleon separation energy plotting, which is useful for nuclear astrophysics. Lastly, 3D plotting which provides a clear view of the distribution of quadrupole deformation throughout the even-even nuclear landscape is available.

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**Poster ID : 186**

**Measurements of Gamma Rays from Be-7 and Li-7 Inelastic Scattering**

Ab-initio methods have been successful in describing the structure of light nuclei using realistic nucleon-nucleon interactions, but more experimental data is needed for light unstable nuclei. Recent no-core configuration interaction calculations have been performed for transition strengths in Be-7. These include a predicted value for the M1 transition strength and progress toward a lower limit for the E2 electromagnetic transition strength. The E2 transition strength has never before been measured. To measure the E2 transition strength, a Coulomb Excitation experiment was performed using a radioactive beam of Be-7 at the University of Notre Dame. Be-7 was produced using the superconducting solenoids TwinSol, where Be-7 was separated from other beam products made in the production reaction. A beam of Be-7 ions were scattered off a gold target and the gamma rays from the inelastically scattered ions were detected using six clover Ge detectors. The most recent results for the E2 transition strength and its comparison to the no-core configuration interaction approach will be shown. In addition, an experiment on the mirror nucleus Li-7 was performed using a stable beam. The E2 transition strength of Li-7 has previously been measured and will provide an important benchmark for our Be-7 analysis. A discussion of the Li-7 compared to the Be-7 will be presented, and extensions of this experimental method to further light unstable nuclei will also be discussed.

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Recent Technical Developments at JYFLTRAP and Atomic Mass Measurements for Neutrino Studies

The JYFLTRAP Penning trap setup [1] at the IGISOL-4 facility, Jyväskylä, Finland, is routinely used for atomic mass measurements and to provide clean samples of ions for decay spectroscopy studies. So far masses have been measured using the time-of-flight ion-cyclotron resonance (TOF-ICR) technique [2] and clean samples have been prepared with sideband cooling technique [3] or sometimes utilizing high-resolution Ramsey cleaning technique [4].

Recent introduction of the phase-imaging ion-cyclotron resonance (PI-ICR) technique has given a significant edge over both TOF-ICR and the Ramsey cleaning technique: With the PI-ICR technique, roughly one order of magnitude improvement in resolution has been demonstrated [5]. We are currently in process to commission this technique at JYFLTRAP. Another important development at JYFLTRAP is the construction of a multi reflection time-of-flight (MR-TOF) separator/spectrometer. The MR-TOF device is based on the University of Greifswald design [6] but has been fully characterized with simulations in Jyväskylä.

In this contribution, I will focus in these two upgrades and show the most recent results. The new techniques will be useful for future Q-value measurements relevant for neutrino physics at JYFLTRAP. As an example of these studies, I will discuss recent results of the beta-decay and the double beta decay Q-value measurements of $^{96}$Zr [7] and beta-decay Q-value of $^{71}$Ge [8]. These are typical experiments for neutrino physics often requiring high-resolution cleaning.

References:

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Enhanced Exotic Beam Capabilities at TwinSol

Many astrophysical events such as novae and X-ray bursts are triggered by reactions on exotic nuclei. Determining the properties of these nuclei and their reaction rates are critical to understanding these astrophysical explosions. The Twin Solenoid (TwinSol) exotic beam facility has been in operation at the University of Notre Dame for two decades producing energetic (2-6 MeV/u) beams of many light exotic nuclei. Recently there have been a number of upgrades that have enhanced these capabilities, which will help facilitate measurements of astrophysical interest. New production target designs and materials are being explored along with adjustments in the solenoid positions and optics, in situ adjustable tuning irises, and advanced ion optical studies of beam trajectories. Initial results from these upgrades along with possible future enhancements will be presented.

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Optimized Gamow Shell Model Interaction for psdf Shell Nuclei

Gamow Shell Model (GSM) which provides a consistent many-body description of nuclear bound states, resonances and scattering states can be considered an open-quantum system extension of the standard Shell Model. A proper treatment of the coupling to the non-resonant particle continuum is of key importance for it deeply impacts the bulk properties and spectra of weakly-bound nuclei. In this contribution, we investigate a new effective N+NN potential applied for the first time within the GSM framework to describe a variety of structure (bound and unbound) and reaction observables across the whole psdf shell nuclei (A=5-15).

Following the usual prescription, the translationally invariant GSM Hamiltonian is separated into a one-body term and a residual two-body potential. The nuclear (Woods-Saxon with spin-orbit) and Coulomb single-particle potentials which describe the field of the 4He core have been adjusted to reproduce n+alpha and p+alpha scattering phase shifts, as well as the single-particle energies in 5He and 5Li. Similarly the two-body residual interaction is split into a nuclear part and a Coulomb part. In this study, we have developed a finite-range NN residual interaction, which consists of central, spin-orbit and tensor parts. Each term is expressed as a sum of three Gaussian form factors with different ranges: a short range to account for the repulsive nucleonic core, a long range that essentially mimics the one-pion exchange potential and a medium range. The interaction has been optimized to the ground state energies of the He, Li and Be chains and we will present the first GSM-spectra of bound and weakly-bound isotopes in the psdf shell region.

Statistical studies have been carried out to assess statistical uncertainties and correlations between parameters and/or predicted observables.

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Investigation of the Nuclear Structure of $^{33}$Al Through beta-decay of $^{33}$Mg to Probe the Island of Inversion

Some nuclei far from the valley of stability have been found to have ground state properties that are different than those naively expected from the nuclear shell model. The term "island of inversion" is used to refer to a region of the chart of the nuclides around the N = 20 closed shell nucleus $^{32}$Mg where large ground-state deformations occur in association with intruder configurations from the f5/2 shell. The nuclear structure of transitional nuclei, in which the normal and intruder configurations compete, can be used to test theoretical models used to explain the inversion mechanism. One such transition occurs along the N = 20 isotones, where neutron-rich $^{33}$Mg is known to have a deformed ground-state configuration, while $^{34}$Si displays a normal one. Previous studies [1, 2] of the intermediate N = 20 isotope $^{33}$Al have yielded conflicting results regarding its structure. In the present work, $^{33}$Al was studied through the beta-decay of $^{33}$Mg to clarify these discrepancies.

A low-energy radioactive beam of $^{33}$Mg was delivered at a rate of $10^4$ ions/s by the Isotope Separator and Accelerator (ISAC-I) facility at TRIUMF. Data were collected with the GRIFFIN [3] high-purity germanium gamma-ray spectrometer coupled with the SCEPTAR plastic scintillator beta particle detector. The majority of the data were collected in a cycled mode (with a period of ~10 s beam on, 1.5 s beam off) to provide sensitivity to all of the $^{33}$Mg, $^{33}$Al, $^{32}$Al beta-n daughter) and $^{33}$Si half-lives. The high efficiency of the GRIFFIN detector provides new gamma-gamma coincidences to elucidate the excited state structure of $^{33}$Al, and the capability of GRIFFIN to detect weak transitions has provided more complete beta-decay branching ratios for the $^{33}$Mg $\rightarrow^{33}$Al $\rightarrow^{33}$Si decay chain. Results from this analysis will be presented and their significance discussed.

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Studying the Photon Strength Function of $^{97}$Zr Using the $^{96}$Zr(n,g) and $^{96}$Zr(d,p) Reactions

A major barrier in the study of neutron-induced nuclear reactions, which play a critical role in stockpile stewardship and astrophysics, is the impossibility of direct measurements with short-lived radioactive isotopes. Theoretical models can be used to describe these reactions, although the nuclear structure inputs such as the Photon Strength Function (PSF) for these exotic nuclei are often poorly constrained. Recently, a program to investigate the PSF for medium-mass nuclei has begun as a collaboration between Los Alamos National Laboratory (LANL) and Argonne National Laboratory (ANL), combining unique experimental capabilities from both laboratories. At the Manuel J. Lujan Neutron Scattering Center at LANL, The Detector for Advanced Neutron Capture Experiments (DANCE) provides direct measurements of gamma ray cascades from neutron capture reactions on stable or long-lived radioactive nuclei.

At the Argonne Tandem Linear Accelerator System (ATLAS) facility at ANL, single neutron transfer reactions in inverse-kinematics provide complementary data on short-lived radioactive nuclei. The Helical Orbit Spectrometer (HELIOS) is a device that was designed to study transfer reactions in inverse kinematics by detecting the charged ejectiles inside of a large-bore solenoidal magnet. The APOLLO array was designed and built at LANL to be placed inside the magnetic field of HELIOS to measure gamma ray cascades from the nuclear states populated in neutron transfer reactions. As a test case for this research program, the $^{96}$Zr(n,γ) reaction was measured using DANCE and the $^{96}$Zr(d,p) reaction was measured using HELIOS+APOLLO. $^{96}$Zr lies near the light mass peak in the $^{239}$Pu fission spectrum, so neutron capture rates on the neutron-rich Zr isotopes are important for fission applications.

While DANCE provides Multi-Step Cascade spectra from $^{97}$Zr as well as cross section information, HELIOS+APOLLO will provide more detailed nuclear structure information about the intermediate states in $^{97}$Zr. Initial results from the $^{96}$Zr(d,p) and $^{96}$Zr(n,γ) measurements will presented. This work benefited from the use of the LANSCE accelerator facility. Work was performed under the auspices of the US Department of Energy by Los Alamos National Security, LLC under contract DE-AC52-06NA25396.

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Proposed Optical Pumping Schemes for the Determination of Charge Radii of Radioactive Nuclides of Transition Metals

The charge radii and electromagnetic moments of short-lived nuclides of selected elements have been extensively studied using the collinear laser spectroscopy (CLS) technique [1,2]. However, data are still sparse for many elements, including the 1st and 2nd row transition metals, Ti-Zn and Zr-Cd respectively. These rows span the N=28-50 neutron magic numbers and encompass the debated subshell closure at N=40 [3], as well as the region of rapid development in collectivity beyond N=40 [4]. The deficiency in charge radii data is due in part to difficulties in the production of radioactive isotopes of these elements. Other reasons include unreachable wavelengths from a laser system, weak atomic transition strengths, non-favorable atomic configurations to extract nuclear properties and/or a scatter of initial atomic populations over dense atomic energy levels. A promising method to overcome these difficulties is the manipulation of atomic populations by way of the optical pumping technique to redistribute the populations in favor of laser spectroscopy. This was first realized in the laser spectroscopy of Nb ions [5] and later in other systems [6,7]. Similar measurements are being planned for the transition metals at the BEam COoling and LAser spectroscopy (BECOLA) facility [8] at NSCL/MSU. In this approach, the trapping region of the radiofrequency ion trap is illuminated with laser light, where efficient optical pumping is made possible due to the extended laser-ion interaction time in the trap. An excited state will be selected so that the excited state decays to populate metastable states, from which high-resolution CLS can be performed. A pulsed laser system will be added to the existing BECOLA laser system to enable optical pumping for the manipulation of atomic populations. Possible optical pumping schemes for the 1st and 2nd row transition metals, as well as the expected impact on the CLS measurements will be discussed.

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Penning Trap Mass Spectrometry Q Value Determinations for Highly Forbidden and Low Q Value Beta-decay Processes

Over the last several decades, extremely sensitive, ultra low background beta- particle and gamma-ray detection techniques have been developed. These techniques have enabled the observation of very rare processes, such as double-beta-decay, highly forbidden beta decays e.g. of $^{113}$Cd [1], $^{50}$V [2] and $^{138}$La [3], and the ultra low Q value beta-decay of $^{115}$In to the first excited level of $^{115}$Sn [4]. Half-life measurements of highly forbidden beta decays provide a testing ground for theoretical nuclear models, and the comparison of calculated and measured energy spectra could enable a determination of the effective values of the weak coupling constants [5].

The study of ultra low Q value beta decays provides a means for investigating enhanced atomic interference effects in these low energy decays [6] and has the potential to identify new candidates for direct neutrino mass determination experiments.

We will present the results and current status of Q value determinations for highly forbidden and possible ultra low Q value beta decays. The Q values, corresponding to the mass difference between parent and daughter nuclides, are measured using the high precision Penning trap mass spectrometers LEBIT at the National Superconducting Cyclotron Laboratory, and CPT at Argonne National Lab.

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Helium-Jet Ion-Source Development for Commensal Operation at NSCL/FRIB

Abstract: NSCL is funded by the National Science Foundation to be a national user facility with a mission to provide beams of rare isotopes for researchers from around the world. Hundreds of users come to Michigan State University each year to take advantage of the Laboratory’s facilities and explore the nature of nuclear forces that bind nucleons into nuclei and the role of nuclei in the universe. However, at present, beams of rare isotopes produced by fast fragmentation can only be used in a single experimental end-station at NSCL. The Helium-Jet Ion Guide System (HJ-IGS) project is aimed to provide a commensal rare isotope beams to a user by collecting ions that are not delivered to the primary user. Rare isotopes that are deflected off the ion-optical axis in the A1900 fragment separator will be thermalized in a stopping cell filled with helium gas mixed with aerosols. The gas/aerosol mixture is then transported through a capillary to an ion source, from which it can be made available to various experimental systems. Essential for the implementation of this concept is that the thermalizing cell and the extraction mechanisms are compact and compatible with existing beamline infrastructure.

The proof of principle of this concept was tested using Cf fission fragments at HRIBF, ORNL. Several dozen n-rich isotopes were thermalized, extracted from the cell and identified from decay gamma rays after transporting to a distance of about 100ft. Subsequently, a high voltage system and optics was developed and few were extracted as low energy ion beam.

At NSCL, a new isotope separator with matching optics will be added for producing mass separated ion beam. The eventual goal is to then cool these beams using a RFQ cooler and transport the rare isotopes to one of the low-energy experimental end stations or the NSCL re-accelerator.

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Experimentally Constrained $^{73}\text{Zn}(n,g)^{74}\text{Zn}$ Reaction Rate

Neutron capture reactions are an integral part of heavy element synthesis, and the rates of these reactions need to be understood in order to model potential astrophysical processes that produce heavy elements. Currently, only nuclei at or near stability have experimentally measured neutron capture cross sections, as direct measurements on short-lived nuclei are not possible. The theoretical cross sections used for short-lived nuclei can vary by orders of magnitude, making any modeling of astrophysical processes difficult. The development of indirect measurements to obtain these cross sections has allowed experimental constraints to be placed on what were once purely theoretical values. The most recent, the beta-Oslo method, utilizes the short half-lives of the nuclei of interest by using beta decay to populate highly excited states in the daughter nucleus. A total absorption spectrometer is used to detect the gamma de-excitation of the daughter, and the nuclear level density and gamma strength function of the excited nucleus are extracted. A Hauser-Feshbach statistical model is used to obtain a neutron capture rate that is experimentally constrained, as both the level density and gamma strength function are inputs. The recently constrained neutron capture rate of $^{73}\text{Zn}$ will be presented.

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High-Precision Half-Life Measurement for the Superallowed $\beta^+$ Emitter $^{22}\text{Mg}$

High precision measurements of the $R$ values for superallowed Fermi beta transitions between $J^\pi = 0^+$ and isospin $T=1$ isobaric analogue states allow for stringent tests of the electroweak interaction described by the Standard Model. These transitions provide an experimental probe of the Conserved-Vector-Current hypothesis, the most precise determination of the up-down element of the Cabibbo-Kobayashi-Maskawa quark-mixing matrix, $V_{ud}$, and set stringent limits on the existence of scalar currents in the weak interaction. In order to use the superallowed decays to perform such tests, however, several theoretical corrections must be applied to the experimental data. In particular, many studies of the isospin symmetry breaking correction, $\delta_C$, have been performed with large model dependent variations. Precise experimental determinations of the $R$ values can be used to help constrain the different models used in the calculation of $\delta_C$.

Currently, the uncertainty in the $^{22}\text{Mg}$ superallowed $R$ value is dominated by the uncertainty in the experimental $R$ value. The adopted half-life of $^{22}\text{Mg}$ is dominated by a single high-precision measurement ($T_{1/2} = 3.8755 \pm 0.0012$ s [1]) which disagrees with the only other, and less precise, measurement ($T_{1/2} = 3.857 \pm 0.009$ s [2]) yielding a $\chi^2 / \nu = 4.0$ and resulting in the inflation of the weighted-average half-life by a factor of 2. The discrepancy between these two measurements has been addressed through a new high-precision half-life measurement for $^{22}\text{Mg}$ carried out at TRIUMF’s Isotope Separator and Accelerator (ISAC) facility. This experiment was performed using a $4\pi$ continuous-flow gas proportional counter to detect the beta particles with near 100% efficiency. The resulting $^{22}\text{Mg}$ half-life has been determined to a precision of 0.02%, which is a factor of 3 more precise than the previously adopted world average and resolves the discrepancy between the two previous half-life measurements. In this presentation, the new high-precision half-life measurement for $^{22}\text{Mg}$ and its implications for testing the isospin symmetry breaking corrections in superallowed Fermi beta decays will be discussed.

References:

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Gamma-Gamma Angular Correlations With GRIFFIN

The assignment of spins and parities to excited nuclear states plays an important role in determining nuclear structure. In a γ-γ cascade from an excited nuclear state an anisotropy is found in the spatial distribution of the second γ-ray with respect to the first γ-ray. The anisotropy depends on the sequence of spin values for the nuclear states involved, and the multipoarities and mixing ratios of the emitted γ-rays.

Angular correlations, which are used for the assignment of spins and parities to the nuclear states, thus provide a powerful means to elucidate the structure of nuclei away from stability. The goal of this work was to explore the sensitivity of the new Gamma-Ray Infrastructure For Fundamental Investigations of Nuclei (GRIFFIN) 16 clover-detector gamma-ray spectrometer at TRIUMF-ISAC to such γ-γ angular correlations. The methodology was established using the well-known 4+ → 2+ → 0+ γ-γ cascade from 60Co decay, and optimized through both experimental measurements and Geant4 simulations. Simulations allow the creation of angular correlation templates using the GRIFFIN geometry to provide direct comparisons with experimental data sets.

A first in-beam test of the γ-γ angular correlation measurements with GRIFFIN was performed with a radioactive beam of 66Ga (T1/2 = 9.49(3) hours) from the ISAC facility at TRIUMF. In the daughter nucleus, mixing ratios were measured for the 22+ → 21+ → 0gs+ and 11+ → 21+ → 0gs+ cascades. The results are in excellent agreement with the literature values and the mixing ratio δ = -2.1(2) for the 22+ → 21+ → 0gs+ cascade was determined with improved precision. Also, the high sensitivity to pronounced 0+ → 2+ → 0+ angular correlation was demonstrated.

The ability to assign spins for a 0+ → 2+ → 0+ cascade is important for the 62Ga superallowed Fermi β-decay, as conflicting 0+ and 2+ assignments have been made for the 2.34 MeV excited state in the 60Zn daughter nucleus. This spin assignment has important implications for the isospin-symmetry-breaking correction, δC, in 62Ga superallowed decay.

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Half-Lives of the Neutron-Rich N~82 Isotopes $^{128-130}$Cd and $^{131}$In

The beta-decay half-lives of N=82 nuclei below doubly-magic $^{132}_{50}$Sn$_{82}$ play an important role in the formation and shaping of the second r-process abundance peak. Shell-model calculations for extremely neutron-rich nuclei near the N=82 neutron shell closure that are not yet experimentally accessible have been performed by adjusting the quenching of the Gamow-Teller (GT) operator to reproduce the $^{130}$Cd half-life reported in Ref. [1]. The resulting half-lives for other nuclei in the region for which measurements are available are, however, known to be systematically too long.

Recently, a shorter half-life was measured for $^{130}$Cd by the EURICA collaboration [2] that would largely resolve this discrepancy by scaling the GT quenching by a constant factor for all of the nuclei in the region. However, the reduced quenching of the GT operator implied by these results creates a discrepant half-life for the decay of $^{131}$In [2], prompting a new measurement with the GRIFFIN spectrometer.

Distinguishing between these discrepant half-life measurements for $^{130}$Cd and $^{131}$In is thus of critical importance since the as yet unknown half-lives of other N=82 waiting-point nuclei with $40 < Z < 44$ play a key role in the formation of the A~130 r-process abundance peak.

These half-lives are challenging to measure as this neutron-rich region contains many complicated decay chains due to the presence of significant beta-delayed neutron decay branches and the population of isomeric states with half-lives comparable to the nuclear ground-states. Much of this background can be removed by measuring the time distribution of characteristic gamma-rays emitted following the beta-decay of interest. We have measured the half-lives of $^{128-130}$Cd [3] and $^{131}$In using the newly-commissioned, high-efficiency GRIFFIN gamma-ray spectrometer at TRIUMF.

Our results improve the precision of the $^{128,129}$Cd half-lives and confirm the shorter half-life of $^{130}$Cd reported in Ref. [2]. Details of both the $^{128-130}$Cd and $^{131}$In experiments will be presented and implications of the results discussed.

References:
Precision Half-life Measurements of $^{17}$F and $^{25}$Al at the University of Notre Dame

In recent years, precision measurements have led to considerable advances in understanding in several areas of physics, including fundamental symmetry. The precise determination of $\beta$ values for superallowed mixed transitions between mirror nuclides could provide an avenue to test the theoretical corrections used to extract the $V_{ud}$ matrix element from superallowed pure Fermi transitions. The calculation of the $\beta$ value requires precise and accurate half-life, branching ratio, and Q value. To this end we recently started at the Nuclear Science Laboratory of the University of Notre Dame a program aimed at improving the lifetime of mirror transitions. Our first measurements on $^{17}$F and $^{25}$Al will be presented together with their impact on the $\beta$-value determination of these isotopes.

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In-trap Decay, Recapture and Beam Transport of Recoiling Decay Products at TITAN-EBIT

The ISOL (Isotope Separation On-Line) method is a reliable technique to produce high quality Radioactive Ion Beams (RIBs) and is employed by many facilities worldwide. Limitations of the method revolve around chemical and physical processes related to extraction of the species of interest from the production target, implying that beams of many chemical elements are currently very difficult to produce and specific nuclear states impossible to be selected.

A way to circumvent this limitation, the "recoil-ion trapping" technique allows the production of beams of isotopes that an ISOL facility is not able to provide directly, but can provide a parent species. This technique consists of storing a cloud of the parent ion in an ion trap for long enough that a cloud of the daughter can be created. In this work, we report the first successful in-EBIT (Electron Beam Ion Trap) production of a daughter species from a short-lived nuclide and its delivery to other experimental setups.

A $^{30}$Mg ion beam delivered by the TRIUMF-ISAC facility was stored at TITAN's EBIT for about one half life. An intense electron beam passing through the trapping region provided strong ion confinement, which allowed easy retrapping of the recoiling daughter $^{30}$Al produced in the $^{30}$Mg decay. The ion cloud containing the trapped species was extracted from EBIT and filtered in time-of-flight. Downstream, the ion bunch was injected into TITAN's high resolution Penning trap mass spectrometer, where a precision mass measurement of $^{30}$Al, which was not originally present in the beam delivered to TITAN, was successfully performed.

We characterized the evolution of EBIT trapped contents and its dependence with trap parameters by extracting them into a microchannel plates detector a few meters downstream EBIT, yielding time-of-flight spectra; and observed the in-trap decays of $^{30}$Mg and $^{30}$Al through a set of photodetectors installed around EBIT's view ports. We also explored which conditions were required for a successful beam delivery to the Penning trap. We discuss the details and challenges of this technique which could be exploited by several other RIB facilities, mainly those which employ electron beam ion sources. Given the typical high confinement properties of this kind of device, high beam intensities may be achievable.

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Identification of the First-excited 2p2h Configuration in $^{35}\text{P}$

The excitation energy of deformed intruder states (specifically the 2p2h bandhead) as a function of Z along N=20 is of interest both in terms of better understanding the evolution of nuclear structure between spherical $^{40}\text{Ca}$ and the 'Island of Inversion' nuclei, and for benchmarking theoretical descriptions in this region [1]. At the center of this Island of Inversion the 2p2h neutron excitations across a diminished N=20 gap result in deformed and collective ground states, observed in $^{32}\text{Mg}$. In higher-Z N=20 isotones, 2p2h excitations are not the ground states, but are present in the relatively low-lying level schemes. To determine the excitation energy of the expected 2p2h $\times s_{1/2}^+$ state in $^{35}\text{P}$, the only N=20 isotope for which the 2p2h excitation bandhead has not yet been located, the $^{36}\text{S}(d, \alpha)^{35}\text{P}$ reaction has been revisited in inverse kinematics with the Helical Orbit Spectrometer (HELIOS) [2] at the Argonne Tandem Linac Accelerator System (ATLAS). Earlier attempts to identify this state suffered from a large background in the region of interest arising from contaminants in the target [3]. However, thanks to the unique capabilities of HELIOS, enhanced with a recoil detector setup, it is possible to perform the reaction with a pure $^{36}\text{S}$ beam avoiding the background from the $^{36}\text{S}$ target. First results will be presented, and the implications for the understanding of the evolution of 2p2h excitations along N=20 discussed.

References:

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The $\beta$ Decay of $^{34,35}$Mg and the Structure of $^{34}$Al

Nuclei in the island of inversion, near the $N = 20$ shell closure, exhibit a fascinating behavior where the nuclear ground states show deformed configurations dominated by particle-hole excitations across the neutron shell gap. The $^{31-35}$Mg nuclei are in or at the border of this island displaying intruder ground-state configurations, while the $^{31-35}$Al isotopes are suggested to have mixed ground-state configurations of normal and intruder type and thus serve as a transition from intruder dominated Mg isotopes to the normal ground-state configuration in Si isotopes.

An experiment was performed at the TRIUMF-ISAC-I facility with the goal of populating states in $^{33-35}$Al via the beta decay of $^{33-35}$Mg. A UC x target with laser-ionization from TRILIS was bombarded with 500 MeV protons to produce beams of Mg ions. The ions were transported and implanted onto a moving Mylar tape at the center of the GRIFFIN spectrometer [1]. A set of 20 plastic scintillators (SCEPTAR) was used for beta tagging. This was surrounded by 12 HPGe GRIFFIN-clover detectors for $\gamma$-spectroscopy.

Results obtained from the analysis of the $^{34,35}$Mg decay data from this experiment will be presented. This includes the half-lives of $^{34,35}$Mg and $^{34,35}$Al which clarify current conflicting information in the literature [2].

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Experimentally Constrained $^{92}\text{Sr}(n,g)$ Reaction Rates Relevant to r-process Nucleosynthesis

The ability to accurately model neutron capture reactions is key to further developing our understanding of fundamental nuclear physics and supporting nuclear science applications. The nearly-completed Facility for Rare Isotope Beams (FRIB) will offer a unique opportunity to investigate neutron-induced reactions on short-lived nuclei important to the dynamics of the r-process. This work will develop new techniques to determine cross sections for nuclei that had previously been inaccessible and apply this approach at the National Superconducting Cyclotron Laboratory (NSCL) to make the first experimentally-informed determination of a neutron-capture cross section on a short-lived fission fragment, $^{92}\text{Sr}$.

At the NSCL, a proposed experiment to determine the $^{92}\text{Sr}(n,g)$ cross section through measurement of the statistical properties of the $^{93}\text{Sr}$ nucleus has been approved. The $^{93}\text{Sr}$ nucleus, formed by neutron capture on $^{92}\text{Sr}$, can be produced by the beta-decay of $^{93}\text{Rb}$ and the emitted gamma rays from $^{93}\text{Sr}$ excited states can be studied. From the measurement of the gamma-ray cascade, the nuclear level density and gamma-ray strength function, essential for modeling neutron capture, can be extracted using the Oslo method. This method has been successfully applied to scores of elements, ranging from Fe to the actinide region.

In preparation for the upcoming experiment, gamma rays emitted by the $^{93}\text{Sr}$ nucleus were simulated using the Monte Carlo code DICEBOX, which takes advantage of known energy levels, spins, parities, and branching ratios in combination with a Monte Carlo technique. The simulated gamma cascade will be used to theoretically predict the neutron capture cross section within the Hauser-Feshbach formalism so as to later compare with the cross section obtained using experimentally-determined statistical nuclear properties. As there are currently little nuclear data available for Sr isotopes heavier than A=88, the high energy level density was estimated using systematics of neighboring isotopes via the average spacing for s-wave neutron capture. This was connected to available experimental data at low energy using a constant-temperature level density model, as motivated by previous work on actinide nuclei or those near shell gaps ($^{90}\text{Sr}$ is near N=50). This foundational work and the planned experiment aim to improve predictive reaction theory and provide constraints on the fundamental behavior of nuclei far from the valley of stability.

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Probing the Band-terminating 13/2+ State in 19F via Transfer Reactions on a Nanosecond Isomer

In 19F we have the rare opportunity to probe the nucleon configuration of the proposed terminating state of the K=1/2 ground-state rotational band, the yrast 13/2+, through neutron-transfer reactions on the short-lived 5+ isomer of 18F (162-ns half-life). Such measurements are typically unattainable since direct reactions, such as (d,p), generally prohibit transitions to high-spin states. In this presentation, we report on results from a recent experiment performed at the Argonne Tandem Linac Accelerator System (ATLAS) in which a 14-MeV/u 18F beam with an intensity of about 8-7x10^3 18F/s/μA and purity of 30-20% was produced in-flight via the $^2$H($^1$O,n) reaction in inverse kinematics. The 18F beam was transported to a CD2 target inside the Helical Orbit Spectrometer (HELIOS) where events from (d,p) reactions were observed on both 1+ ground-state and 5+ isomer components of the 18F beam. Angular distributions for states in 19F, including the 13/2+ which is uniquely populated from (d,p) reactions on the isomer, were measured. For states populated from the 18F ground state we find consistent results with previous experiments.

Relative spectroscopic factors were extracted and are in agreement with shell-model calculations. The large value of the l=2 spectroscopic factor of the 13/2+ state in 19F confirms that the angular momentum of the band-terminating state is generated from the alignment of the spins of the valence nucleons.

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EMMATrap: A New Generation of Cryogenic Gas Stopper Based on RF-funnels Ion Extraction and Bunching

We propose the development of an advanced ion-stopping, extraction, and bunching system to gain access to nuclei far from the valley of $\beta$-stability, especially on the neutron-deficient side of the nuclear chart, that are only reachable via nuclear reactions. These stopped, cooled and pulsed radioactive ions will be sent to a Penning-trap for high-precision mass measurements. The proposed system will be installed at the focal plane of TRIUMF’s EMMA recoil spectrometer and is called EMMATrap.

Isotopes of interest are those on the neutron-deficient side such as, Sn-100, Kr-70, Kr-72, and other isotopes close to the p-dripline that are of importance to rp-process network calculations. In addition to pushing out further in the N=82 region of the r-process, with new ARIEL beams EMMATrap will be able to make measurements of nuclei in the relatively unexplored N=126 region of the r-process.

EMMATrap will consist of four main components: A high-density gas stopper cell will be located at the focal plane of EMMA to stop the incoming reaction products. This cell is intended to be operated at cryogenic temperatures to freeze out contamination in the He gas and reduce the possibility of charge exchange. An original compact system of 4 RF ion funnels will be used to extract cooled ions from the stopper cell into high-vacuum conditions and also bunch them. This feature makes the use of a conventional linear Paul trap for ion bunching obsolete thus reducing the time ions spend in manipulation devices. The ion bunch is then injected into a Multi-Reflection Time of Flight (MR-ToF) mass spectrometer, which can either be operated such as to separate masses and remove contaminants, or measure masses to a precision of $\delta m/m \sim 10^{-5}$. If the MR-ToF is operated in ‘cleaning’ mode, the ions of interest are sent to a precision Penning Trap mass spectrometer capable of performing mass measurements to precisions on the order of $10^{-9}$. In a first stage, the stopper cell combined with the RF-funnel ion extraction and bunching, and the MR-ToF will be commissioned in a proof-of-principle experiment to demonstrate the power of the presented system. In a second stage the system will be coupled to the high-precision Penning trap mass spectrometer. The whole setup will be designed to be easily removable to allow the installation of other types of detectors at the focal plane of EMMA for different measurements such as decay spectroscopy.

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The Search for Neutrinoless Double Beta Decays with EXO-200 and nEXO

The Enriched Xenon Observatory (EXO) is an experimental program designed to search for the neutrinoless double beta decay of Xe-136. Observation of this decay would prove that neutrinos are massive Majorana particles (i.e. they are their own anti-particles), and constitute physics beyond the Standard Model. The first phase experiment, called EXO-200, has re-started operation at the WIPP mine in New Mexico, USA, using 200 kg of liquid xenon enriched to 80% in Xe-136 in an ultra-low background time-projection chamber (TPC). The detector performance and response has been thoroughly tested and is well understood. With the EXO-200 detector sensitive searches for neutrinoless and two neutrino double beta decays have been performed along with searches for exotic decay modes and decays to excited states. Some of these searches provided the most stringent limits on these decay modes.

In parallel to the operation of EXO-200, the development of nEXO, a next-generation liquid xenon TPC has started. The nEXO detector will consist of 5T enriched xenon and will be deployed at a selected underground laboratory, ideally the SNOLab facility in Sudbury. Advanced detection technologies are being developed to read out charge and scintillation signals from the xenon TPC, such as charge readout tiles and Si photo multipliers, respectively. With these technologies and the increased target mass, the nEXO detector has the potential to completely probe the inverted neutrino-mass scale. The status of the EXO-200 detector, detector performance, and analysis techniques applied to achieve the current results will be discussed. In addition, current design efforts for the future multi-ton experiment nEXO will be discussed.

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TITAN’s Multiple-Reflection Time-of-Flight Isobar Separator and Mass Spectrometer

At the Isotope Separator and ACcelerator (ISAC) [1] at TRIUMF national laboratory, Vancouver exotic nuclei are produced by the ISOL method also used e.g. at CERN, JYFL and Oak Ridge. The exotic nuclides are separated by a magnetic separator and transported to TRIUMF’s Ion Trap for Atomic and Nuclear science (TITAN) [2]. TITAN is a multi ion-trap system allowing high-precision mass measurements and in-trap decay spectroscopy. Although ISAC can deliver high yields for some of the most exotic species many beams suffer from a strong isobaric background. This background often prevents the high-precision measurement of the species of interest. To overcome this limitation an additional isobar separator based on the Multiple-Reflection Time-Of-Flight Mass-Spectrometry (MR-TOF-MS) technique has been designed and developed for TITAN [3]. Mass separation is achieved using a mass-selective dynamic re-trapping technique after a time-of-flight analysis in an electrostatic isochronous reflector system. Thus isobaric contaminants can be removed before the species of interest is delivered to an EBIT for charge breeding or the measurement Penning trap for high precision mass measurements. Providing additional isobar separation TITAN’s MR-TOF-MS will allow TITAN to pursue its mass measurements approaching the drip-lines, where isobaric contaminations are an increasing challenge. Additionally the MR-TOF-MS will enable mass measurements of very short-lived nuclides (half-life > 1 ms) that are produced in very low quantities (tens of detected ions) on its own. As a broadband tool the MR-TOF-MS can efficiently be used for beam diagnostics and determination of yields or beam compositions.

The device has recently finished its offline commissioning and demonstrated its capabilities for high precision mass spectrometry with resolving powers of up to 190,000 and precisions of m/dm ~ 5 x 10⁻⁷ for a mass measurement of ⁴⁰Ar. In addition high-resolution isobar separation with resolving powers exceeding 25,000 has been shown by spatial separation (more than one FWHM) of the isobars ⁴⁰-Ar and ⁴⁰-K.

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Investigation of Excited 0+ States Populated via a Er-162 Two-neutron Pickup Reaction

Interpreting the nature of excited states in well-deformed nuclei has been an ongoing challenge in our understanding of nuclear structure. Some of the approaches that have been implemented to interpret the occurrence of low-lying excited 0+ states include vibrational excitations in beta-phonons and gamma-phonons, as well as pairing excitations. A further complication is the presence of shape coexistence which can increase the number of low-lying states, and if the shapes undergo mixing that spectroscopic signatures can become ambiguous. The N=90 region is just such a case with a well-known rapid change in the ground state shape from N=88 to N=92. However, one of the difficulties in resolving the nature of these states is that there is an absence of data, particularly for excited 0+ states, in the rare earth region.

Two-neutron transfer reactions are ideal for probing 0+ → 0+ transitions in deformed nuclei. One of the intriguing features of the rare-earth region are the strongly-populated 0+2 states that emerge in both (p,t) and (t,p) two-neutron transfer reactions into N=90 nuclei $^{154}$Gd and $^{152}$Sm [1]. Excited 0+ states in $^{160}$Er have been studied via the $^{162}$Er (p,t) reaction at the Maier-Leibnitz Laboratory in Garching, Germany using 22 MeV and 24 MeV proton beams supplied by a Tandem Van de Graaff accelerator. Reaction products were momentum-analyzed with a Quadrupole-3-Dipole magnetic spectrograph.

The variance in the cross section of these low-lying excited 0+ states, with the 0+2 state population around 18% of the ground state strength, suggests a special character for this state which is not consistent with a beta-vibration. In fact, evidence points towards the nature of this state being more consistent with a shape coexistence picture. Final results of the relative population of the excited 0+ states in $^{160}$Er will be presented, and placed into context with similar experiments in the N=90 region.

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Constraining the Single-particle Asymptotic Normalization Coefficient in Neutron-rich Nuclei

Understanding the spectroscopic properties of unstable nuclei near shell closures and r-process waiting points can help constrain nuclear structure models used to predict properties of even more exotic nuclei. Reliably extracting spectroscopic information is difficult in exotic, neutron-rich nuclei partly due to an unknown bound-state potential. However, a method to constrain this potential has been proposed by Mukhamedzhanov and Nunes [1]. In this approach, a single-neutron transfer reaction, such as (d,p), measured at different energies should constrain the single-particle asymptotic normalization coefficient, ANC. At low energies (~5 MeV/u), the ANC for the nucleus can be extracted, and when combined with the same reaction at higher energies (~40 MeV/u), spectroscopic factors can be extracted with uncertainties dominated by experimental statistics rather than the shape of the bound-state potential. To test the proposed combined reaction method, the ⁸⁶Kr(d,p) reaction was measured for the first time in inverse kinematics with a 35 MeV/u beam at the National Superconducting Cyclotron Laboratory with the ORRUBA and SIDAR arrays of silicon strip detectors coupled to the S800 spectrometer. The data from this higher energy measurement were analyzed in combination with published results of ⁸⁶Kr(d,p) at 5.5 MeV/u [2]. Analysis using finite-range adiabatic wave approximation shows that the single-particle ANC can be constrained. The details of the analysis and prospects for measurements with neutron-rich beams will be presented.

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Ground State Electromagnetic Moments of $^{53}\text{Fe}$

Nuclear structure studies around $^{56}\text{Ni}$ nucleus with $N = Z = 28$ are critical since $^{56}\text{Ni}$ is considered to be a soft core [1]. In this region of interest, the nuclear magnetic-dipole moment, and the electric-quadrupole moment, $Q$, of $^{53}\text{Fe}$ were determined for the first time.

The $^{53}\text{Fe}$ beam was produced by fragmentation of a 160-MeV/nucleon $^{58}\text{Ni}$ beam in a Be target at the NSCL at MSU. The $^{53}\text{Fe}$ beam was selected using the A1900 fragment separator [2], thermalized in a gas stopper [3], and extracted at an energy of 30 keV. The Fe$^+$ beam was then transported to the BECOLA facility [4] and bunched-beam collinear laser spectroscopy was performed to measure the atomic hyperfine structures (hfs) [5].

Ion beams of the transition-metal Fe are known to be notoriously difficult to produce at ISOL facilities due to long release times from thick targets. The novel scheme of in-flight separation followed by gas stopping was used in the present study for the first time for laser spectroscopy. This is a major step forward in laser spectroscopy experiments and complements the well-established capabilities at ISOL facilities [6].

The nuclear magnetic and quadrupole moments of $^{53}\text{Fe}$ were determined from the A and B hyperfine coupling constants respectively, which were obtained from a fit to the hfs.

The multi-configuration Dirac-Fock method was used to calculate the magnetic and electric field gradients to deduce the magnetic and quadrupole moments from A and B respectively. The obtained nuclear moments agree with shell model calculations with GXPF1 interaction, which support the softness of $^{56}\text{Ni}$. The theoretical interpretation as well as the experimental details will be discussed.

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Coulomb Excitation Study of $^{78}$Kr Using TIGRESS and SPICE

Neutron-deficient krypton isotopes close to the N=Z line occupy a region of the nuclear chart with several competing shape minima. In the fpg shell the single-particle orbitals display significant energy differences depending on deformation. This leads to notably different shape configurations within a few hundred keV, leading to the phenomena of shape coexistence. Consequently, different deformations become the dominant configuration with the change of just a couple of nucleons.

Data suggest a smooth transition in the krypton isotopes, from stable $^{78,80}$Kr displaying prolate ground-state configurations, towards oblate N=Z $^{72}$Kr [1]. A significant degree of mixing between competing prolate and oblate structures appears to be present in each case, making the identification of the underlying configurations rather complex. As a result, rudimentary observables such as energy levels and branching ratios alone cannot hope to fully interpret these nuclei. Hence, one must ascertain an exhaustive set of transition strengths and static moments, to evaluate and deconvolve both the underlying intrinsic structures and degree of mixing.

One such study of $^{78}$Kr was performed by Becker et al. [2] using a safe Coulomb excitation reaction. Both transition strengths and static quadrupole moments were reported, leading to the conclusion of a prolate deformed nucleus with mixed oblate rotational bands. Most notably, the suggestion of a $K=0$ band coexisting at low excitation energy with an as-yet unidentified 0+ band-head is in contradiction to the assignment of these states as a $K=2$ structure [3-5]. Further measurements will be essential to clarify this situation.

A Coulomb excitation study of $^{78}$Kr was performed at TRIUMF’s ISAC-II facility utilizing the TIGRESS HPGe clover array. The SPICE detector was also present for detection of internal conversion electrons. Results from our independent Coulex analysis will be presented, which will either support the previous observation or provide much needed additional information to understand the structure of this region.

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Direct Mass Measurements of Neutron-deficient Isotopes of Bi, Po, At, Rn, and Fr at RIKEN/SlowSHE

The SlowSHE facility at RIKEN uses a traveling wave RF carpet, cryogenic gas cell located after the GARIS-II gas-filled recoil separator to thermalize fusion-evaporation products. A series of RF multipole traps accumulate and cool ions extracted from the gas cell, after which they are sent to a multireflection time-of-flight mass spectrograph (MRTOF) for analysis with a typical mass resolving power of R_m=150,000.

The system is nominally intended for mass measurements of trans-fermium isotopes. The system, however, was commissioned using higher cross-section reactions. As part of the commissioning the reaction system $^{165}$Ho($^{48}$Ca, X) was utilized. From these reactions, more than 20 neutron-deficient isotopes of elements from Bi through Fr were analyzed.

In this study the gas cell was operated at a cryogenic temperature near 150 K with room temperature equivalent He pressure of 100 mbar. Unexpectedly, all radioactive isotopes - even isotopes of the alkali element Fr - were determined to have been extracted from the gas as doubly-charged ions.

We will present the results of these mass measurements and discuss the implications of the observation that all species are extracted as multiply-charged ions.

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Gamow-Teller Beta-decay Studies within DFT-rooted No-Core Configuration-Interaction Model

Multi reference Density Functional Theory involving projection techniques is a no-core many-body approach that provides wave function with rigorously treated symmetries enabling, in turn, global calculations of transition rates for various nuclear reactions [1]. By applying configuration interaction (CI) technique the wave function can be further dressed with correlations by admixing self-consistent deformed particle-hole configurations [2,3]. It can be applied to any nucleus, irrespectively on its mass and parity number. Moreover, unlike the other existing CI models, it attempts to describe physics of finite nuclei starting from an intuitive and powerful concept of spontaneous symmetry breaking. Hence, it gives a unique opportunity to discuss emerging complex patterns in terms of simple deformed single-particle (s.p.) Nilsson levels which are primary building blocks of the formalism. First applications of the DFT-rooted No-Core Configuration-Interaction (NCCI) models to the structure [2,3] and gamma [3] and beta [2] decay rates are very encouraging to perform further tests of the formalism. During the presentation, after brief introduction of the model, I will proceed to show its application to compute Gamow-Teller (GT) response taking into account the impact of the isospin symmetry breaking. I will demonstrate that the model is capable to grasp main features of the GT strength distribution starting from very light p-shell systems, through sd-shell nuclei up to the heaviest N≈Z nuclei underlining its universality. As representative examples I will show recent results on the GT strength distribution in 9Li mentioning experimental problem of correct association of BGT [4-6], in 20Ne and 24Mg compared to the experiment and shell-model calculations [7], and, eventually, on the superallowed GT beta decay of 100Sn widely studied in [8]. Finally, I will demonstrate how the complex patterns of GT strength and GT resonances correlate with the underlying s.p. structure and particle-hole excitations among deformed states.

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**Precision Mass Measurements of Neutron-Rich Co Isotopes Beyond N=40**

For many years, the region near Z=28, N=40 has been a subject of great interest for the nuclear structure community due to spectroscopic signatures in $^{68}$Ni suggesting a subshell closure at N=40. Mass surfaces and their derivatives provide a complementary approach to shell structure investigations via separation energies, and mass measurements can therefore play an important role in understanding shell structure in the region of $^{68}$Ni. Penning trap mass spectrometry has provided precise measurements for a number of nuclei in this region, however a complete picture of the mass surfaces has so far been limited by the large uncertainty remaining for nuclei with N>40 along the iron and cobalt chains. Here we shall present the first Penning trap measurements of $^{68,69}$Co, performed at the Low Energy Beam and Ion Trap facility at the National Superconducting Cyclotron Laboratory, and discuss the importance of these measurements for understanding the evolution of nuclear structure in the region of $^{68}$Ni. In particular we compare with predictions of ab initio valence-space in-medium SRG calculations, based on two and three-nucleon forces, which agree well with experimental ground-state and two-neutron separation energies throughout the Ni and Co isotopic chains.

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**Spectroscopic Strengths of Low-lying Levels in $^{18}$Ne**

Much effort has been made to understand the origins of $^{18}$F in novae. Due to its relatively long half-life (~2 hours), $^{18}$F can survive until the nova envelope is transparent, and therefore can provide a sensitive diagnostic of nova nucleosynthesis. It is likely produced through the beta decay of $^{18}$Ne, which is itself produced (primarily) through the $^{17}$F(p,$\gamma$) reaction. Understanding the direct capture contribution to the $^{17}$F(p,$\gamma$) reaction is important to accurately model it. As such, the spectroscopic strengths of low-lying states in $^{18}$Ne are needed. At the University of Notre Dame a measurement of the $^{17}$F(d,n) reaction has been performed using a beam produced by the TwinSol Low energy radioactive beam facility. The neutrons were detected using a combination of Versatile Array of Neutron Detectors (VANDLE) and UoM Deuterated Scintillat or Array (UMDSA). Data will be shown and preliminary results discussed.

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Validating the (d,pγ) Reaction as a Surrogate for (n,γ) on Rare Isotopes Using the 95Mo(d,pγ) Reaction

Nearly half of the elements between bismuth and iron were created in an explosive stellar environment through the rapid neutron capture process (the r process). The r process forms heavy nuclei through neutron capture on lighter nuclei and their subsequent β decay. Until recently it was thought that (n,γ) and (γ,n) exist in equilibrium until late times in the r process, which limits the impact of individual (n,γ) rates on the final abundance pattern. However, Mumpower et al. [1] have shown that the persistence of (n,γ)<->(γ,n) equilibrium depends on the site in which the r process occurs, so individual neutron capture rates can strongly influence the final abundance pattern. Unfortunately, the exotic nuclei which participate in the r process are too short-lived to be made into targets. Nor can the (n,γ) rates on these nuclei be directly probed in inverse kinematics, as neutron targets do not exist. It is thus necessary to validate a surrogate reaction for (n,γ) to indirectly extract these cross sections for r-process nuclei. The (d,pγ) reaction has been identified as a promising (n,γ) surrogate reaction, and a complete theoretical treatment of the formation of the compound nucleus, including the elastic and inelastic breakup of the deuteron, has been developed by Potel et al. [3]. Gamma branching ratios are determined by fitting Hauser-Feshbach parameters to the experimentally-extracted γ-ray emission probabilities. These are then used to extract a neutron capture cross section. This method has been applied to the 95Mo(d,pγ) system in normal kinematics, for which the neutron capture cross section is known [4]. We report on the successful effort to validate (d,pγ) as a surrogate for (n,γ).

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References:

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Development of Co-existing Xe-129 and Xe-131 Masers with Time-separated Feedback Scheme for the Xe Atomic EDM Search

The non-zero electric dipole moment (EDM) of a particle directly violates time reversal invariance, hence violates the CP-symmetry. Since the contribution to the EDM from the Standard Model (SM) of particle physics is undetectably small, a finite value of the EDM would evidence the CP-violation due to new physics beyond the SM, which is essential in explaining the matter excess in our Universe.

To find and figure out what new physics appears beyond the SM, the measurement of EDMs in several different physical systems is mandatory. As already stressed in Ref. [1], improvements in upper limits on EDMs for diamagnetic atoms should play an important role in the study of new physics in the hadron sector. In order to improve the current experimental upper limit on the Xe atomic EDM, $4.1 \times 10^{-27}$ ecm [2], monitoring the spin precession frequency to a nHz precision is required. For such an extreme precision, we introduce a nuclear spin maser with an active feedback scheme, which elongates the spin precession time to infinity [3]. We also introduce co-existing Xe-129 and Xe-131 spin masers in order to reduce systematic errors arising from drifts in the magnetic field and in the Xe-polarized Rb interaction. (Note that the polarized Rb atoms are indispensable both for the spin-exchange optical pumping and for the observation of spin precession of Xe).

Our latest study indicated that the Rb spin, which is considered to adiabatically follow the direction of Xe spin and thus to serve as an indicator of the Xe spin precession, is also influenced by the feedback field for the maser. It may cause the frequency instability of the masers due to the frequency pulling effect [3]. In order to eliminate systematic errors arising from drifts in the amplitude of the feedback field, we recently developed time-separated feedback (TSFB) scheme. In the TSFB scheme, the observation and the feedback field application are separated in time. The feedback field is generated based on the data in the observation period, thus leading the maser operation free from the effect of the feedback field. In this presentation, the frequency characteristics and the long-term stability of the co-existing Xe-129/Xe-131 masers with TSFB scheme will be reported. References:


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Towards Electron Cooling of Highly Charged Ions for Precision Mass Spectrometry

The exact knowledge of nuclear masses is an essential prerequisite for a wide range of studies in radioactive isotope science. Precision mass measurements on radionuclides provide important inputs for nucleosynthesis theory and broaden our understanding of the evolution of the nuclear shell structure far from stability. The TITAN facility at TRIUMF deploys a multi-ion-trap setup to perform precision mass spectrometry on rare nuclei. At TITAN radioactive Singly Charged Ions (SCI) are charge bred in an electron beam ion trap and the mass of the resultant Highly Charged Ions (HCI) is measured in a Penning trap mass spectrometer. The utilization of HCI may improve the statistical mass uncertainty as the cyclotron frequency in the Penning trap increases linearly with the ions’ charge state. However, the precision gain by using HCI is mitigated by the enlarged beam energy spread resulting from the charge breeding process.

In order to reduce the ion bunch’s energy spread prior to injection into the mass measurement Penning trap, a new Cooler PEning Trap (CPET) is currently being commissioned off-line and will thereafter be inserted into the TITAN beamline. In CPET we will perform electron cooling of radioactive HCI. In this approach electrons are stored in a nested potential well and self-cool via emission of cyclotron radiation in the trap’s 7T strong magnetic field, thus forming a dense, room-temperature plasma. The electron plasma serves as a cooling medium by forcing simultaneously trapped HCI to undergo multiple Coulomb scattering with cold electrons. The electrons are supplied by an off-axis electron gun located in the trap’s magnetic fringe field. As the electron trajectories are considerably deflected by the magnetic fringe field a set of specialized charged-particle optics is required to facilitate effective electron loading. We discuss the optimization of the off-axis electron gun and the electron injection into CPET’s strong magnetic field. Further, the creation of an electron plasma with more than 10^7 particles in a nested potential well is reported and recent progress towards cooling of stable SCI - as an essential step on the route to electron cooling of short-lived HCI - is presented.

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Optimization of the Measurement Conditions in the Laser-microwave Double Resonance for the Atoms Injected into Superfluid Helium

We develop laser spectroscopic technique combining superfluid helium (He II) and laser–radio frequency (RF)/microwave (MW) double resonance aiming at the nuclear structure studies of the unstable nuclear atoms with low production yields and short lifetimes. Highly energetic ion beams are caught in a narrow region in He II by virtue of the high density of He II, and immediately neutralized. The depleted zone called “atomic bubble” is formed around the atoms in He II [1]. Consequently, the excitation spectrum is significantly blue-shifted compared with the emission one.

This enables us to measure a Zeeman or hyperfine structure splitting with a high sensitivity and a high precision by applying laser-RF/MW double resonance methods to the atoms.

So far, we succeeded in the observation of laser MW double resonance (LMDR) signals for $10^4$ pps Rb ion beams supplied by RIKEN Projectile-fragment Separator (RIPS) with an energy of 66 MeV/u [2]. However, the LMDR signal intensities were not high enough to realize a high-precision measurement of the hyperfine structure splitting for the nuclei with lower production yields.

In general, we need higher laser and MW power to obtain higher resonance peak heights in LMDR spectroscopy. On the other hand, a stronger laser beam causes larger backgrounds due to laser stray light. Thus it is required to experimentally find the combination of the most suitable laser and MW powers. In order to estimate the optimal measurement conditions, as a preliminary experiment, we measured the change of LMDR signal intensities for different laser powers using a glass cell which contains Rb vapor and He buffer gas where a collisional transfer occurs between $5p^2P_{1/2}$ and $5p^2P_{3/2}$ states. We observed D2 line (from $5p^2P_{3/2}$ to $5s^2S_{1/2}$ states) fluorescence while we excited the D1 transition (from $5s^2S_{1/2}$ to $5p^2P_{1/2}$ states) where the D2 and D1 lines are similar to the absorption and the emission lines, respectively, in He II. This provides an inverted analog of the method in a He II environment. Moreover, we investigated the effect of residual magnetic fields on the center frequency shifts and the widths in microwave resonance spectra by intentionally applying external magnetic fields in a perpendicular direction to the laser axis. We report results and details of this experiment.

References:

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Role of Clustering and the Competing Reaction Modes in the Decay of Alpha Conjugate Composite System $^{20}$Ne$^*$

The clustering effects in the light mass alpha conjugate system $^{20}$Ne$^*$ has been explored within the collective clusterization process of dynamical cluster decay model (DCM), build on the basis of quantum mechanical fragmentation theory (QMFT) [1]. The QMFT supports the alpha clustering in the alpha conjugate nuclear system $^{20}$Ne at excitation energy corresponding to $^{16}$O cluster decay threshold, given by the Ikeda diagram [2], taking into consideration the proper pairing strength in the liquid drop energies. 

Further, the clustering aspects in $^{20}$Ne$^*$ alpha conjugate composite system formed in $^{10}$B+$^{10}$B reaction has been explored within QMFT based DCM, and quite interestingly, the results show that at the higher excitation energies clustering scenario changes drastically. The np-$\alpha$ type clusters (where n and p denote the neutron and proton, respectively), namely $^6$Li, $^{10}$B and $^{14}$N clusters, are preformed strongly compared to $\alpha$-$\alpha$ type clusters due to decrease in pairing strength at the high temperatures. Moreover, the binary symmetric fragment or cluster i.e. $^{10}$B has large preformation value at higher excitation energy compared to at resonant energy. This result is in conformity with observations within the relativistic mean-field calculations [3] for intrinsic excited states of $^{20}$Ne and the energy density functional calculations [4] which demonstrate similar type of findings for $^{20}$Ne. The details of clustering effects within DCM has been elaborated in the ref. [5]. Also, the decay of $^{20}$Ne$^*$ composite system has been studied in reference to the available experimental data [6] for Z = 5, 6, 7 fragments with the consideration of quadrupole deformation and orientation of nuclei. The study revealed the presence of competing decay paths of fusion fission (FF) and deep inelastic orbiting (DIO) which are of compound and non- compound nucleus origin, respectively. In ref. [5], the DIO cross-section contribution in the total cross-section ($\sigma_{\text{tot}}$) has been evaluated empirically. In the present work, we intend to calculate the contribution of DIO in the $\sigma_{\text{tot}}$ for Z = 5, 6, 7 fragments, within the formalism of DCM.

References:

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Radioisotope Beam Production at TRIUMF in the ARIEL Era

As the only ISOL facility worldwide, ISAC-TRIUMF is routinely operating targets under particle irradiation in the high-power regime in excess of 10 kW. TRIUMF’s current flagship project ARIEL, Advanced Rare IsotopE Laboratory, will add three new target stations providing isotopes to the existing experimental stations in ISAC, to a dedicated collection station as well as for chemical post-processing and subsequent use for medical imaging and treatment. In addition to the existing 500 MeV, 50 kW H- driver from TRIUMF’s cyclotron, ARIEL will make use of a 35 MeV, 100 kW electron beam from a newly installed superconducting linear accelerator. Together with additional 200 m of RIB beamlines within the radioisotope distribution complex, a high-resolution mass separator, a gas-filled RFQ cooler, as well as an EBIS charge-state breeder, this will put TRIUMF in the unprecedented capability of delivering three RIB beams to different experiments, while producing radioisotopes for medical applications simultaneously – enhancing the scientific output of the laboratory significantly. General characteristics of the high-power target and beam delivery technology at ISAC and ARIEL will be presented, showing the opportunities and limitations. Moreover, the current status of the facility as well as the path to completion and ramp-up will be discussed.

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Development of the High-sensitive Atomic Laser Spectroscopy Using Superfluid Helium for the Study of Nuclear Structure of Rare-isotopes

We are developing a laser spectroscopy technique utilizing superfluid helium (He II). This technique is named OROCHI which stands for Optical RI-atoms Observation in Condensed Helium as Ion-catcher. In our technique, highly energetic ion beams produced at accelerator facilities are injected into He II. Injected ions are neutralized during their stopping process and stopped as atoms isolated in He II. We perform spin polarization production using an optical pumping method. The Zeeman/hyperfine structure splitting of the stopped atoms is directly measured using laser-RF (radio frequency)/MW (microwave) double resonance method to determine their nuclear spin/electromagnetic moment, respectively.

There are two characteristic advantages to use He II as described below. Most of ions are stopped within a few mm<sup>3</sup> owing to high density of He II. When atoms are introduced in He II, the center wavelength of optical absorption spectra becomes different from that of emission spectra. Thus we can detect emitted fluorescence with low background. Taking full advantage of the characteristics of He II, we conducted a series of experiments using<sup>84-87</sup>Rb ion beams (66 MeV/u, 10<sup>3</sup>-10<sup>4</sup> pps) delivered from the RIPS beam line at RIKEN so far[1]. We successfully observed double resonance spectra of Rb isotopes using He II as a stopper for the highly energetic ion beams. However, we also found that the S/N ratio of the obtained spectra was not high enough for the application to rare isotopes. In particular, the background signals due to an inefficient laser stray light suppression made both fluorescence detection and double resonance spectra observation difficult. In order to overcome this difficulty, we have introduced a new developed detection system to make use of the characteristic optical spectra of atoms in He II.

Recently, we performed an online experiment to show the validity of our development quantitatively. We investigated the detection limit of the current system by observing fluorescence using<sup>85</sup>Rb beam whose intensity was monitored. In addition, we observed laser-RF double resonance spectra with a higher S/N ratio than that of the previous experiment. The obtained result suggested that, if we can achieve 80% of the spin polarization, the applicable beam intensity could be reduced by a factor of 6. In this presentation, we will give the detail of the experiment and discuss the obtained results.

References:

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Development of a Low-background Detection System for the Laser-induced Fluorescence From the Atoms Injected into Superfluid Helium

We are developing a laser spectroscopy technique named OROCHI (Optical RI-atom Observation in Condensed Helium as Ion-catcher). This technique is expected to be capable of the study of low-yield nuclei whose production rate is less than 100 pps.

In OROCHI experiment, accelerated ion beams are injected into superfluid helium (He II). Owing to the high density of He II, most of injected ions are stopped and neutralized. We observe laser-induced fluorescence (LIF) from the stopped atoms and measure the Zeeman splitting using laser-radiofrequency double resonance method and the hyperfine splitting using laser-microwave double resonance method. We can derive nuclear spins and moments. He II is also utilized as the host matrix of laser spectroscopy. When atoms are immersed in He II, it is known that absorption and emission spectra have different center wavelengths [1]. Therefore, LIF can be optically isolated from laser stray light that usually causes a high background signal in spectra.

We observed LIF from $^{85-87}$Rb isotopes with a typical beam intensity of $10^4$ pps and double resonance spectra using an LIF detection system (LDS) in the previous experiment [2]. However, we found that the LDS did not sufficiently reduce the laser stray light. In order to utilize the characteristic of the atomic spectra in He II, more effectively we have developed a new LDS which makes it possible to detect the LIF with an extremely low background. In the new LDS, a combination of a bundled optical fiber and a monochromator able to efficiency remove laser stray light was introduced.

We confirmed the background suppression capability of the new LDS in an online experiment using $^{85}$Rb ion beam with a typical beam intensity of $10^3$ pps. In this experiment, we correlated the LIF counts with the number of injected $^{85}$Rb into He II to evaluate S/N ratio quantitatively. As a result, we succeeded in the drastic reduction of laser stray light background by a factor of 600. Since, however, the new LDS sensitivity to LIF turned out to be reduced by factor of 10 compared with the previous one, we undertake further modification of the LDS to improve its LIF collection efficiency towards the application to lower-yield nuclei. We will show the detail of development of the LDS and the obtained results in the experiment. We will also discuss a new idea for improving LDS.

References:

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The oxygen nuclear magnetic resonance (NMR) serves as a powerful tool to gain the knowledge about atomic-scale properties of a vast variety of the oxygen-containing materials. Such studies, however, have been so far complicated by different objective limitations such as low natural abundance of the NMR-active isotope $^{17}$O, difficulties and costliness of the isotopic enrichment etc. Alternatively, the $^{17}$O and $^{19}$O isotopes with known values of nuclear moments would seem appropriate to be used in $\beta$-ray-detected nuclear magnetic resonance ($\beta$-NMR) studies. However, the use of these isotopes also has strong disadvantages such as low beam purity in case of proton-rich $^{17}$O and long lifetime of $^{19}$O leading to the insufficient NMR-signal intensity. All these aspects make neutron-rich $^{21}$O a good candidate for probing the oxygen-sites in condensed matters. As a first step in such studies, the electromagnetic nuclear moments of this isotope must be determined.

In the present research, we conducted the measurements of the ground-state magnetic dipole and electric quadrupole moments of $^{21}$O isotope. The experiment was performed using the projectile-fragment separator RIPS at the RIKEN RIBF facility. A secondary beam of $^{21}$O was produced in the projectile fragmentation reaction involving neutron pick-up reaction of a $^{22}$Ne beam at 69A MeV on Be target. The isotope separation through the momentum and momentum-loss analyses by RIPS was applied to select the isotope of interest, which were then implanted into a stopper material.

Electromagnetic moments were determined by means of the $\beta$-NMR method in combination with the adiabatic fast passage (AFP) technique. The nuclear moments of the implanted isotope are deduced from the value of a resonance frequency, which is measured by detecting the change in the beta-decay asymmetry of nuclei of interest. This change, in turn, is induced by the application of an oscillating magnetic field, whose frequency is swept across the Larmor frequency.

Details of the experiment as well as the obtained results will be discussed in the presentation.

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An Electrostatic Ion Trap for Physics Beyond-the-standard-model Search

One of the possibilities to study fundamental interactions and the underlying symmetries is via precision measurements of the parameters of beta decay of trapped radioactive atoms and ions, thus probing the minute experimental signal that originates from possible tensor or scalar terms in the weak interaction of beyond-the-standard-model nature. For precision measurements of this correlation, ion traps are convenient tools since the recoiling nuclei, subsequent to the beta decay, are at sub-keV energies. We have embarked on an experimental program to study the beta-neutrino correlation by measuring the decay of trapped, light, radioactive ions inside an Electrostatic Ion Beam Trap (EIBT). This is a novel application of such a device, extensively used in atomic and molecular physics, exhibiting several advantages compared to other commonly used trapping schemes in terms of concept, efficiency and ease of operation. The first nuclide under study is $^6$He, ionized, stored and bunched in an Electron Beam Ion Source (EBIS), specially designed together with the manufacturer for enhanced efficiency. The study of $^{16}$N is also envisaged.

The entire apparatus was constructed at the Weizmann Institute of Science (WIS), with commissioning experiments performed using $^4$He, CO and O ions. The specific radioactive isotopes to be studied, $^4$He and $^{16}$N, will be produced by energetic neutrons impinging on a porous, hot BeO target via the $^9$Be(n,α)$^6$He and $^{16}$O(n,p)$^{16}$N reactions, respectively. The fast neutrons (14 MeV) are delivered by a commercial (D+T) neutron generator. At the next stage, the program will utilize the neutrons from the intense ~1 mA, 5.5 MeV D beam of the newly constructed superconducting LINAC, “SARAF Phase I”, at the Soreq Nuclear Research Center (SNRC), Israel.

The construction of the target room for SARAF-I will take place during 2017. The entire setup, including the EIBT, the EBIS and the high-temperature oven with the porous BeO target (for $^4$He and $^{16}$N) will be transferred from WIS to the new target room in SNRC during the current year in order to continue experiments there.

In this conference, we will present the results of commissioning runs and progress in this project, including first $^4$He yield measurements and concrete plans at the SARAF-I accelerator facility and future possibilities at SARAF-II.

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Peeking into the Stars: Approaching the Stellar $^{124}$Xe(p,γ) Reaction Using the ESR Storage Ring

Charged-particle reactions, like (p,γ) or (a,γ), play a crucial role in many different astrophysical scenarios. Their direct measurement is key for nucleosynthesis model predictions, but is, however, typically hampered by very low cross sections and the availability of intense radioactive ion beams. In this contribution, a novel, powerful method will be presented, which aims at overcoming these limitations: we used decelerated cooled beams in the ESR storage ring at GSI to measure the $^{124}$Xe(p,γ) reaction directly. This reaction belongs to the p process flow and serves as a perfect benchmark for this method.

The stable $^{124}$Xe beam was accelerated in the UNILAC and the SIS18 to high energies of about 100 AMeV, fully stripped and injected into the ESR. The beam was subsequently decelerated and then cooled with the electron cooler: we were thus able to push the beam energy down to the Gamow window while maintaining brilliant energy resolution. For the first time, this enabled a direct reaction measurement at the astrophysically relevant energies. In the future, this method will allow reaction studies using radioactive ion beams in or close to the Gamow window at low beam intensities and low cross sections.

This contribution will describe the technique and first results will be presented. Also, an outlook towards future studies and techniques will be given.

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Dynamical Aspects of Sub-barrier Fusion in $^{18}\text{O}+^{12}\text{C}$ Reaction

The availability of radioactive ion beams due to advanced accelerator technology, provides the opportunity to study the fusion process with neutron rich nuclei. The experimental studies with neutron rich projectile show the fusion enhancement compared to the case of $\beta$-stable projectile. The studies show that the fusion enhancement is best studied at sub-barrier and near barrier energies. The mass asymmetric reaction with exotic nuclei $^{15}\text{C}+^{232}\text{Th}$ [1] and $^{124,132}\text{Sn}+^{40}\text{Ca}$ [2] at sub-barrier energies show fusion cross-section enhancement. It is important to study the reactions in light mass region with exotic nuclei, which are estimated as probable heat source in the neutron star crust [3]. The experimental study of near barrier and sub-barrier fusion reaction of exotic $^{18}\text{O}$ beam with $^{12}\text{C}$ target shows the fusion enhancement [4].

Recently, we have studied the clustering prospect and decay of light mass composite system $^{28}\text{Si}^*$ formed in $^{16}\text{O}+^{12}\text{C}$ reaction [5]. At experimental excitation energy [6], in addition to $x\alpha$-type ($x$ is an integer) clusters ($^{12}\text{C},^{16}\text{O},^{24}\text{Mg}$) the symmetric cluster $^{14}\text{N}$ (np-$x\alpha$ type, where n, p are neutron and proton number respectively) has maximum preformation probability in the decay of $^{28}\text{Si}^*$. In the present work, we intend to investigate the dynamical aspects such as potential energy surface, preformation profile of fragments and barrier characteristics in the decay of $^{30}\text{Si}^*$ formed in $^{16}\text{O}+^{12}\text{C}$ reaction at sub-barrier and near energies within the quantum mechanical fragmentation theory based dynamical cluster decay model (DCM) [7]. The preliminary results show that in potential energy surface, the minima is more pronounced for $^{13,14}\text{C}$ and $^{16,17}\text{O}$ ($x\alpha$ and xn-$x\alpha$ type clusters) compared to symmetric fragment ($^{14}\text{N}$, np-$x\alpha$ type cluster) in contrast to the results for $^{28}\text{Si}^*$. These facts are further observed in the preformation profile of different fragments. Further calculations for the fusion cross-section, having contribution from light particles and intermediate mass fragments, are in progress, and their comparison with the available experimental data [4], accordingly.

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The Development of the New Off-line 2 Isotope Mass Separator at ISOLDE, CERN Within MEDICIS-Promed

In order to further develop ion sources and target units a non-radioactive test laboratory, Off-line 2, is currently under construction at ISOLDE, CERN. Off-line 2 will also allow for improvements of beam manipulation techniques using a Radio-Frequency Quadrupole cooler and buncher (RFQCB). The improvements will then be applied and used at the CERN-MEDICIS facility and at the ISOLDE on-line facility when producing radioactive isotopes. This project is one of the 15 projects currently in development in MEDICIS-Promed.

MEDICIS-produced radioisotope beams for medical applications is a Marie Curie Innovative Training Network which will train a new generation of 15 entrepreneurial scientists. The network will be able to bridge academia, industry, research institutions and hospitals together in order to produce, transport, manufacture and deliver compounds of radioisotopes used for imaging and cancer treatments. The production of dedicated medical batches for radiopharmaceuticals together with development towards $^{11}$C-based hadron therapy treatments will be performed using radioactive ion beams at the new CERN-MEDICIS facility which is an extension of the ISOLDE facility.

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Study of Fusion Cross Sections of $^4$He Induced Reactions Forming $^{60}$Zn*, $^{60}$Ni* and $^{60}$Fe* Compound Nuclei

The latest development in the radioactive ion beam facilities all over the world has offered an excellent opportunity to investigate in detail the nuclear reaction dynamics of unexplored regions of the periodic table and novel properties associated with the dynamics of exotic nuclear systems can be understood accordingly. Upcoming prospects of atomic nuclei formed in the reactions induced by neutron rich isotopes or by taking rare isotopes as target have generated much interest in nuclear physics research, experimentally as well as theoretically. The decay of number of Compound Nuclei (CN) has been studied successfully using Dynamical Cluster Decay Model (DCM) [1]. In this Quantum mechanical theory (QMFT) based DCM approach; the neck length ($\Delta R$) is the only free parameter. We generally rely on the experimental data to optimize the value of $\Delta R$. But, in some of our previous studies successful attempts have been made to predict fusion cross sections ($\sigma_{\text{fus}}$) within DCM. Heavy ion reactions induced by loosely bound or stable projectiles having the same incident energy on different targets have been studied extensively, within DCM [2]. In these studies, the value of $\Delta R$ is fixed empirically for the given projectile at a given choice of projectile energy. $\sigma_{\text{fus}}$ for all other reactions induced by the same projectile at the fixed incident energy on different targets are estimated/predicted using the same value of $\Delta R_{\text{emp}}$. In the present work we have utilized this idea to study the decay of $^{60}$Zn*, $^{60}$Ni* and $^{60}$Fe* which were not explored experimentally due to the non-availability of the required stable targets. To fix $\Delta R$ empirically for the present study, we have chosen $^4$He induced reactions with targets $^{64}$Zn, $^{48}$Ca and $^{44}$Ca, for which experimental data is available at various incident energies ($E_{\text{lab}}$) $\sim$10-17 MeV [3]. This value of $\Delta R$ is then used further to predict the $\sigma_{\text{fus}}$ of the CN i.e. $^{60}$Zn*, $^{60}$Ni* and $^{60}$Fe* formed in the reactions $^4$He+$^{56}$Ni, $^4$He+$^{56}$Fe and $^4$He+$^{56}$Cr, respectively. However, the main purpose of present work is not only to predict the $\sigma_{\text{fus}}$ of the CN, but also to explore the effect of excitation energy in the decay process.

References:

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High-spin Magnetic Dipole Bands in As Isotopes Near A ~ 80

High-spin sequences of negative-parity magnetic dipole transitions, built on a 13/2− bandhead with Ex > 2 MeV, have been reported in several nuclei of the A ~ 80 region; e.g., 75,77As, 77,79,81Br, and 79,81,83,85Rb [1, 2, 3]. These bands are strikingly similar with strong ΔI = 1 transitions, and no ΔI = 2 ones. The sequences decay toward the low-lying positive- or negative-parity bands in all the nuclei mentioned above [3]. These bands in 77As and 77,79,81Br have been interpreted as 3-qp bands built on the πg9/2 x νg9/2 x ν(pf) configuration, and are characterized by a high-K quantum number. Due to similarities of the physical observables for these bands with magnetic rotational bands, the bands in 77,79,81Br have also been suggested to be associated with the shears mechanism [4]. Very recently, however, a band with similar characteristics has been observed in 75As [1], but has been interpreted as being associated with a novel mode of excitation, the so-called “stapler” mode. In the latter mode, the valence neutron in the g9/2 orbital is responsible for closing the stapler and generating the higher-spin states of the band [1]. It is of interest to explore the presence of a similar structure in the heavier As isotopes and to understand the evolution of the 3-qp high-K intruder bands or shears/stapler bands. With this motivation, high-spin states in 79As, populated in deep-inelastic reactions using Gammasphere at ATLAS, have been studied. New results on the level structure of 79As nucleus will be presented.

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References:

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Thermal neutron capture gamma-ray spectroscopy and prompt gamma-ray spectroscopy of fission fragments are powerful tools to obtain detailed nuclear structure information for nuclides close to stability and medium mass neutron-rich isotopes. These nuclear structure information can be used for the test of nuclear models, as well as for the extraction of quantities important for nuclear applications. The power of coupling a high-efficiency Ge detector array with an intense pencil-like neutron beam provided by the ILL reactor, has been recently demonstrated by the success of the EXILL (EXogam at ILL) campaign. This success led to the installation of permanent setup at ILL, the new instrument FIPPS (FIssion Product Prompt Spectrometer). In its first phase, it consists of an halo-free pencil neutron beam incident on a target surrounded by an array of 8 Ge clovers. This setup has been recently commissioned in Dec. 2016 and it is presently being exploited for a variety of (n,\gamma) experiments. Also fissile and radioactive targets will be used. In a second phase it will be complemented with a recoil spectrometer based on a gas filled magnet. This will increase the sensitivity and selectivity for nuclear spectroscopy of fission products and enable fission studies of the correlation between excitation energy, angular momentum and kinetic energy. After a review of the most significant physics output of the EXILL campaign, the FIPPS instrument will be described. The present performance of the setup will be shown, together with an summary of the results of the first experimental campaign. Future perspectives and physics opportunities will be discussed.

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Fast-timing Investigation of Neutron Rich $^{136}$Te and $^{137}$Te

Unexpected variations of the shell structure and collective phenomena arise in the vicinity of exotic neutron-rich shell closures such as $^{78}$Ni and $^{132}$Sn. Therefore nuclei with few valence particles outside of the doubly magic core provide valuable information on the single-particle energies and give insight into the onset of collectivity. They also provide useful knowledge about nucleon-nucleon effective interactions and allow testing theoretical models. Tellurium isotopes with two protons outside of the 50 shell are key nuclei to study the evolution of shell structure and the onset of collectivity in the $^{132}$Sn region. The collectivity of $^{136}$Te, which couples a proton and a neutron pair to the $^{132}$Sn core, was investigated by means of Coulomb excitation studies [1] yielding a very low $B(E2; 2^+ \rightarrow 0^+)$ strength of $208(29)$ e$^2$fm$^4$. This low value is at variance with the transition rates in Xe and Ba isotopes and is not well reproduced by shell model calculations, being comparable to the $B(E2; 2^+ \rightarrow 0^+)$ strength in $^{134}$Te $N=82$ isotope. A later beta-decay preliminary study [2] using the ATD method [3] to measure the $2^+$ lifetime provided a $B(E2; 2^+ \rightarrow 0^+)$ strength value of $245(50)$ e$^2$fm$^4$, in better agreement with the systematics and the theoretical calculations. Due to the configuration of Te isotopes, certain nuclear properties like the excitation spectra can be well described in the seniority scheme; however this is not the case for transition rates between nuclear states that need a more detailed investigation.

We report on measurements performed during the EXILL-FATIMA campaign at the ILL in Grenoble. Prompt-fission was induced by cold neutrons on Am and Pu targets at the PF1 beam line of the reactor. Gamma-ray spectroscopy and fast-timing measurements were carried out with the EXILL-FATIMA mixed array of Ge and LaBr$_3$(Ce) detectors [4]. We discuss lifetime measurements of the excited states in the even-even $^{136}$Te, providing a crosscheck for first $2^+$ state, together with a re-examination of the value obtained in the beta-decay studies [2]. Transition rates to the ground state, and a comparison to the systematics, are also given. We report for the first time lifetimes of higher excited states in $^{136}$Te, and spectroscopy information on $^{137}$Te with preliminary lifetime values.

References:


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Examining the astrophysical site of r-process nucleosynthesis by reverse engineering nuclear properties from rare earth abundances

The rapid neutron capture process (r-process) is responsible for the production of the heaviest elements in nature. However, the question of the astrophysical site(s) of r-process nucleosynthesis remains one of the most challenging open problems in all of physics. Although core collapse supernovae had previously been widely accepted as the relevant site, recent studies have implicated neutron star mergers to be a leading candidate. Conclusive statements regarding the astrophysical site are difficult to make due to a limited knowledge of nuclear physics far from stability. Current and future radioactive beam facilities will aid in this endeavor by providing new and updated nuclear data to be used in astrophysical simulations. We describe recent developments in the method of "reverse engineering" nuclear properties using well established observational data for the rare earth elements. This new theoretical framework is intended to be used in combination with recent and future measurements to gain new insights into the astrophysical site of the r-process.

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Over the years we have conducted a series of experiments with beta-delayed proton emitters of astrophysical interest by stopping the radioactive isotope beam of interest into a stack of Si detectors of various segmentations [1-6]. In these studies a realization was made that shrinking the physical detection volume of elements in Si detector does not reduce the beta-background enough to study the beta- delayed particle emission in the typical energy range of astrophysically interesting decays (E_p ~ few hundred keV). This led to efforts to further reduce the beta-background through development of a novel detector, AstroBox, based on Micro Pattern Gas Amplifier Detector (MPGAD) technology [7].

Based on this initial development we have built and commissioned an upgraded version of this detector, AstroBox2 [8]. The major change to the first version of the detector is the change of geometry of the MPGAD pad structure. The earlier cylindrical symmetry of the pads has been replaced by a set of rectangular pads that are arranged into a geometry along the beam axis to improve implantation control. In addition the new detector setup has several technical improvements that enhance the overall usability of the detector and associated equipment.

In this presentation we give description of the AstroBox2 detector and discuss the results of the first measurements with beta-delayed proton emitters 23Al and 31Cl. In these experiments we have suppressed the beta-background down to 100 keV or below to allow unambiguous measurement of low-energy beta-delayed protons from these emitters in the astrophysical region of interest around 100-500 keV.

References:

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Towards Cold HCIs for Precision Experiments in Nuclear Physics

Highly Charged Ions (HCIs) are useful for the manipulation of both ions and beams of ions. Their enhanced net charge can facilitate acceleration, enhance the purity of beams, and increase the capabilities of certain experiments. For instance, the precision of nuclear mass measurements using Penning trap mass spectrometry scales with the charge. At TRIUMF’s Ion Trap for Atomic And Nuclear science (TITAN) we use HCIs to enhance the precision for measurements of short-lived nuclei, but it can be further improved by rapidly cooling the HCIs to reduce their kinetic energy spread.

Since many of the conventional cooling methods used for neutral or singly charged ions are no longer feasible for a trapped sample of HCIs, we are currently commissioning offline a Cooler Penning Trap (CPET). CPET is a cylindrical Penning trap designed to trap electrons and HCIs in the same region, such that the electrons can sympathetically cool the HCIs. In order to thus cool HCIs, we need to construct a “nested” trap potential in which the oppositely charged particles overlap spatially. It will be important to optimize the cooling rate of the HCIs in order to study short-lived nuclides. Once the ions have cooled, we then will extract the ions for mass measurement.

We have constructed an offline Penning trap composed of a 7 T magnet and a series of ring electrodes. Our recent progress includes trapping and cooling ~10^7 electrons into a nested potential within our trap. Moreover, a stable ion source has been installed to inject singly charged ions. Considerations for shaping the potential with our ring electrodes such that it can load electrons while both trapping and ejecting ions will be addressed, as well as the strategies we have implemented to facilitate the manipulation and detection of electrons inside of the trap using cost-effective custom-designed hardware solutions. Systematic tests of the offline setup are being performed using a control and data acquisition system based on Labview and C++. Next we will co-trap electrons with ions for the purpose of demonstrating offline cooling of singly charged ions in CPET. Once cooling of SCI has been optimized, we will install CPET into the on-line beam line, characterize it with stable HCI, and then commission it with short-lived HCIs. I will discuss the status and outlook of CPET.

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Beta-decay Study of the $T_z = -2$ Proton-rich Nucleus $^{20}$Mg

For explosive hydrogen burning environments such as classical novae and type I x-ray bursts, our current understanding of nucleosynthesis and energy generation in these astrophysical scenarios is limited by the uncertainties in particular thermonuclear reaction rates. The $^{15}$O($\alpha, \gamma$)$^{19}$Ne($p, \gamma$)$^{20}$Na reaction sequence is a key breakout path from the hot CNO cycle into the rapid proton capture process. The $\beta$ decay of the drip-line nucleus $^{20}$Mg gives important information on key astrophysical resonances in $^{20}$Na, which are relevant to the reaction rate. A detailed $\beta$-decay spectroscopic study of $^{20}$Mg was performed by a continuous-implantation method. A detection system was specially developed for charged-particle decay studies [1], giving improved spectroscopic information including the delayed proton energies, the half-life of $^{20}$Mg, the excitation energies, the branching ratios, and the log $\beta$ values for the states in $^{20}$Na populated in the $\beta$ decay of $^{20}$Mg. A new proton branch was observed and the corresponding excited state in $^{20}$Na was proposed. The large isospin asymmetry for the mirror decays of $^{20}$Mg and $^{20}$O was also well reproduced. To resolve the long-standing problem about the astrophysically interesting 2645 keV resonance in $^{20}$Na convincingly, a higher-statistics measurement may still be needed [2].

References:

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Radiation-damage of Single-crystal Diamond Detectors in Swift Heavy Ion Beams

The excellent properties of diamond (high charge carrier mobility and large lattice displacement energy) allow to develop fast and radiation-hard particle detectors for timing and tracking applications. Single-crystal diamond detectors fabricated by Chemical Vapor Deposition were irradiated with swift heavy ion beams in the energy range of 100-150 MeV/u at the National Superconducting Cyclotron Laboratory at Michigan State University. The degradation of the detector performance was monitored during irradiation by the output signal amplitude. After exposure to a particle fluence of $10^{13}$/cm$^2$, the diamond samples were characterized by the Transient Current Technique to understand the effect of the beam induced damage in the charge transport properties.

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Identification of Fission and Fragmentation Products from $^{238}$U at 80 MeV/u

The acceleration of heavy beams like Uranium-238 to intermediate energies allows us to produce a wide range of nuclei by projectile fragmentation and in-flight fission using the coupled cyclotron facility at the National Superconducting Cyclotron Laboratory, NSCL. The population of multiple overlapping charge states for fragments produced from the heaviest beams, such as uranium and lead, makes the ability to unambiguously identify isotopes challenging. Adequate resolution for atomic mass, A, element number, Z, and charge states, q, was found for A up to approximately 200 from the fragmentation of Pb at 85 MeV/u using a Si PIN stack telescope in coincidence with measurements of the time-of-flight [1]. A recent measurement of projectile-like and medium-mass nuclei produced from the fragmentation and fission of a 80 MeV/u $^{238}$U on beryllium targets using the A1900 fragment separator coupled to the S800 analysis line demonstrated that we can extend this technique to resolve proton number up to Z=94 at the NSCL and future FRIB. This capability will allow us to extract the cross sections for fragments with Z around 30-94 and give insight into whether the NSCL accelerating uranium into an energy regime where the cross sections are independent of projectile energy.

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Correlations within the Non-equilibrium Green's Function Method

Non-equilibrium Green's function (NGF) method is a powerful tool for studying the evolution of quantum many-body systems. Different types of correlations can be systematically incorporated within the formalism. The time evolution of the single-particle Green's function is described in terms of the Kadanoff-Baym equations. In the current work, I first focus on introducing the correlations in the infinite nuclear matter and then in a finite system. Starting from the Harmonic oscillator Hamiltonian, by switching on adiabatically mean-field and correlations simultaneously, a well-defined ground state of a correlated system is arrived at within the NGF method.

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Astrophysical S-factor of $^{13}$C($\alpha$, n)$^{16}$O Reaction and Effect of -3 keV Subthreshold Resonance

The $^{13}$C($\alpha$, n)$^{16}$O reaction is a neutron generator in asymptotic giant branch stars and is considered as the main source of neutrons for the s-process. At low energies (around 140-230 keV) where this reaction is important, the cross sections are dominated by -3 keV subthreshold resonance corresponding to $1/2^+$ (6.356 MeV) level in $^{17}$O. Several direct and indirect measurements have been performed so far [1-3], however, in the low energy region, still there are controversies about the S-factor obtained in different studies. Furthermore, uncertainties are also associated with the position of $1/2^+$ state and in a recent work it is suggested to be a real resonance at 4.7 keV [4]. In this contest, we will present our R-matrix based calculations [5] of S-factor for $^{13}$C($\alpha$, n)$^{16}$O reaction and thereby put a limit on the Asymptotic normalization coefficient of -3 keV resonance. The effects on S-factor of considering $1/2^+$ state as a real resonance at 4.7 keV, will also be presented.

References:

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An Updated Hi-Res Beta-Decay Study of Neutron-Rich $^{74}$Cu

The beta-decay of the neutron-rich isotope $^{74}$Cu has been studied using three high-purity Germanium clover detectors at the Holifield Radioactive Ion Beam Facility at Oak Ridge National Laboratory. A high-resolution mass separator greatly improved the purity of the $^{74}$Cu beam by removing isobaric contaminants, thus allowing decay through its isobar chain to the stable $^{74}$Ge at the center of the LeRIBSS detector array without any decay chain member dominating. Using coincidence gating techniques, 121 gamma-rays associated with $^{74}$Cu were isolated from the collective singles spectrum. Eighty-seven of these were placed in an expanded level scheme, and updated beta-feeding level intensities and log (ft) values are presented based on multiple newly-placed excited states up to 6.8 MeV. The progression of simulated Total Absorption gamma-ray Spectroscopy (TAGS) based on known levels and beta feeding values from previous measurements to this evaluation are presented and demonstrate the need for a TAGS measurement of this isotope to gain a more complete understanding of the $^{74}$Cu decay scheme.

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Total Absorption Spectroscopy of Neutron-rich Nuclei Around the A=100-110 Mass Region

Accurate modeling of the r-process requires knowledge of properties related to the beta decay of neutron-rich nuclei, such as beta-decay half-lives and beta-delayed neutron emission probabilities [1]. These properties are related to the beta-decay strength distribution, which can provide a sensitive constraint on theoretical models. Total absorption spectroscopy is a powerful technique to accurately measure quantities needed to calculate the beta-decay strength distribution. In an effort to improve models of the r-process, the total absorption spectra of neutron-rich nuclei in the mass region around A=100-110 were recently measured using the Summing NaI(Tl) (SuN) detector at the NSCL in the first ever total absorption spectroscopy measurement performed in a fragmentation facility. Total absorption spectra will be presented and the extracted beta-decay feeding intensities will be compared to theoretical calculations.


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Reaction Mechanism Dependence of the Population and Decay of $^{10}$He

Measurements of neutron unbound systems allow for stringent tests of theoretical nuclear structure models at extreme neutron-to-proton ratios. It was recently suggested that the decay of broad neutron unbound states would be sensitive to the incoming channel wavefunction. Thus, the extended wavefunctions of halo nuclei could significantly affect the observed decay energy spectra for broad neutron unbound resonances. Experimental evidence for such an effect had been suggested in the case of $^{10}$He. Its ground state resonance decaying to $^{8}$He+n+n+ exhibited a shift of about 500 keV when populated in a proton removal reaction from $^{11}$Li compared to the transfer reaction $^{4}$He(t,p). In order to test this effect we measured the $^{10}$He ground state resonance in two reactions using beams with different wavefunctions. We compared the decay energy spectrum of $^{10}$He populated in a three-proton removal reaction from the (non-halo) nucleus $^{13}$B with the spectrum from the one-proton removal reaction using the halo-nucleus $^{11}$Li. The decay energy spectra were reconstructed from the measured momenta of the $^{8}$He fragment and two coincident neutrons. The experiments were performed at the Coupled Cyclotron Facility of the NSCL with the Sweeper magnet and the MoNA-LISA array.

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**Poster ID : 342**

**Lifetime Measurement of O-26**

An interesting property of some neutron-unbound systems is true two-neutron emission where the neutrons are emitted simultaneously as opposed to a sequential decay through an intermediate state. Since neutrons are only affected by the angular momentum barrier, the timescale for this process is much shorter than for two proton emission which is dominated by the Coulomb barrier. One such case is O-26 where a very low decay energy was measured and the two valence neutrons are expected to occupy d-wave orbitals. Also, the ground state of O-25 is located 700 keV higher. In a first experiment, the MoNA collaboration extracted a lifetime of 4.5 +/- 1.5 (stat) +/- 3 (syst) ps with a confidence level of 82% (Z. Kohley et al. PRL 110:152501, Apr 2013). Recently, an experiment dedicated to measuring the O-26 lifetime in order to improve the confidence level of the measurement was performed at NSCL. The experiment utilized a newly developed segmented target which increased the statistics without degrading the resolution. Preliminary results will be presented.

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**Poster ID : 343**

**Necessity of Theoretical and Experimental Study on Abrasion-Fission**

In-flight fission is one main production mechanism at new generation of rare isotopes beam facilities as RIKEN, FRIB, FAIR. Models (such as LISE++ 3EER [1], PROFI[2]) based on the geometrical abrasion approach [3] and excitation energy formalism [4] are used for fast calculation of production yield in Abrasion-Fission. These models do not take into account primary beam energy, do not consider energy dissipation processes important for intermediate energies and heavy targets. In this work more sophisticated JQMD Ver.2 [5] in the PHITS 2.88 package [6], which simulates dynamical system of colliding nuclei, has been used to calculate fissile pre-fragment mass and excitation energy distributions. These calculations show drastic importance of input channels as primary beam energy and target choice comparing to the geometrical abrasion approach, and indicate on necessity on theoretical development suitable for fast calculations. On the other hand Abrasion-Fission is very complicated mechanism for experimental study in order to compare with theoretical predictions due to a large number of fissile nuclei. Also it is necessary to identify simultaneously both fission fragments (A,Z,q) with measurement of their momentum vectors in order to try to reestablish parent fissile nucleus (A,Z,E'). Plans to use the High Rigidity Spectrometer proposed for construction at FRIB will be discussed in the context of in-flight fission study.

**References:**


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Shape Coexistence in $^{66}\text{Ni}$

Much attention has been paid to the experimental description of shape coexistence in $^{68,70}\text{Ni}$, in part because of the parallel calculations that could account for the observed features of these nuclei. In this presentation, data will be presented and discussed that underlie the notion that comparable shape coexistence is present in $^{66}\text{Ni}$ [and $^{72}\text{Ni}$] as well. Data from beta decay, direct transfer reactions, knock-out reactions, and multinucleon transfer reactions will be presented along with both previous and recent theoretical calculations.

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