

# ISOLDE Workshop and Users meeting 2019

Thursday, 5 December 2019 - Friday, 6 December 2019

CERN



## Book of Abstracts



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## Welcome

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## EPIC workshop summary talk

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The process of replacing the beam dumps at ISOLDE presents a unique upgrade opportunity that would significantly increase the capability and capacity of the facility. This workshop was initiated to bring together members of the ISOLDE User community and CERN responsible teams to exchange ideas on the possible future upgrades of the ISOLDE facility. Any significant upgrade in the infrastructure at ISOLDE will require financial input from the partner countries in the ISOLDE Collaboration. This will necessitate a well-defined project including the preparation of a Conceptual Design Study and report, which will allow the community to apply for funding of sub-projects of EPIC. One of the goals of this workshop is to define working groups to prepare the Conceptual Design Study covering both the technical requirements and scientific justification. This presentation briefly summarizes the main aspects of EPIC, along with a summary of the conclusions of the workshop and outline the next steps.

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## Reaccelerating Rare Ions Beams at GANIL

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The SPIRAL (Système de Production d'Ions Radioactifs en Ligne) facility (now SPIRAL1) has been in operation since 2001. The description of the facility and the physics results after a decade of its running are presented in Ref. (1). More recently a new target ion source (FEBIAD + Carbon target) has been installed and the charge breeder has been upgraded. These has been implemented considering all the safety measures required by the French nuclear safety authorities.

We will present the status and future perspectives with ISOL beams (low and high-energy Rare Ion beams at GANIL from SPIRAL1 and SPIRAL2-Phase1 using the Super Separator Spectrometer (S3). The talk will then mainly focus on the physics program.

1) A. Navin, F. de Oliveira, P. Roussel-Chomaz, and O. Sorlin J. Phys. G: Nucl. Part. Phys. 38 (2011) 024004

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## The Nuclear Physics Program at TRIUMF

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The ISAC radioactive facility at TRIUMF supports a wide range of nuclear physics, including tests of fundamental physics and symmetries, nuclear astrophysics and applied programs. The ARIEL upgrade program will enable new and more research opportunities. The talk will provide an overview of current program and future opportunities, as well as the status of the ARIEL project

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## Stopped and Reaccelerated Beam Physics at FRIB: Present and Future

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While the construction of the Facility for Rare Isotope Beams (FRIB) at MSU nears completion and the commissioning of the heavy-ion linear accelerator is well underway pre-FRIB Nuclear Science continues to be pursued at NSCL's Coupled Cyclotron Facility. A common feature of NSCL and FRIB are the delivery of fast, stopped, and reaccelerated beams. Experiments using the latter "ISOL" type beams have become a major contributor to the Nuclear Science program and will continue to do so at FRIB.

In this presentation I will provide a brief status update on FRIB and then focus on stopped and reaccelerated beams capabilities and on ongoing research and future opportunities with such beams at FRIB.

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## Status and perspectives for medical isotope production at MEDICIS

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The MEDICIS (Medical Isotopes Collected from ISOLDE) facility is a new and unique facility located at CERN (Switzerland) dedicated to the production of non-conventional radionuclides for research and development in imaging, diagnostics and radiation therapy, with very high specific activity.

CERN-MEDICIS has been commissioned in September 2017 and delivered its first radionuclides in December 2017. Since then, the facility is shipping novel radioisotopes for medical research to hospitals and scientific institutes in Switzerland and across Europe.

Since its commissioning, the CERN-MEDICIS facility has shown the feasibility of providing radionuclides such as Tb-155, Er-169 and Yb-175 for innovative medical research. For that purpose, the facility used either the proton beams from ISOLDE, a CERN nuclear physics facility, or sources provided by external institutes being part of the MEDICIS collaboration. In the first case, the 1.4 GeV proton beams delivered by the CERN Proton-Synchrotron Booster impinge on a target usually made of tantalum or uranium-carbide in which spallation reactions occur. In the second case, which is currently the case during LS2, targets are irradiated either with protons in a cyclotron or with neutrons in a nuclear reactor. In both cases the radionuclide of interest is produced in the irradiated target which is transferred to the MEDICIS facility. The target is heated up to high temperatures (up to 2000°C) to allow for the diffusion and effusion of the atoms out of the target and subsequently ionized. The ions are accelerated and sent through an off-line mass separator. The radionuclide of interest is extracted through mass separation and implanted on a thin metallic foil. After collection, the batch is measured by gamma-spectrometry and prepared to be dispatched to a research center. This presentation will give an overview of the facility during 2019 and its perspectives.

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### The LISA Marie Curie ITN

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LISA (Laser Ionisation and Spectroscopy of Actinides) is a new Marie Curie International Training Network that aims to train the next generation of atomic, nuclear and laser scientists by conducting research to increase our understanding of the atomic and nuclear properties of the chemical elements known as the actinides. Of long-standing interest to the fields of fundamental atomic and nuclear physics, this research is an essential prerequisite for unravelling the structure of the superheavy elements at the end of Mendeleev's table. Furthermore, actinide research is required for the effective production, identification and handling of these elements, and is thus a necessary foundation for our goals of understanding and exploiting the potential for practical applications of the actinides in the fields of medical physics, nuclear applications and environmental monitoring. Our consortium of world-leading experts in radioactive ion beam research and applications, laser spectroscopy, scientific laser technologies (industrial partners) and nuclear and atomic theorists will recruit and train 15 doctoral students. LISA will form a cohesive and symbiotic collaboration for training young scientists in the pursuit of the following research objectives: Develop laser-based actinide ion beam production and purification techniques; develop laser technology; measurement of ionization potentials and electron affinities; extract atomic and nuclear properties from laser spectroscopy studies; enhance the prospects for direct use of the actinide isotopes themselves (theranostic applications), or the application of techniques for their detection (environmental monitoring). Here, a general overview of the scope, structure and timeline of the LISA project will be provided.

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### MIRACLS: The Multi Ion-Reflection Apparatus for Collinear Laser Spectroscopy

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In the study of short-lived radionuclides, Collinear Laser Spectroscopy (CLS) plays an important role as it reveals nuclear ground state properties such as spin, electro-magnetic moments and mean-square nuclear charge radii [1, 2].

To access exotic radionuclides with very low production yields, the Multi Ion-Reflection Apparatus for Collinear Laser Spectroscopy (MIRACLS) is currently being developed at ISOLDE. This novel approach will significantly improve the experimental sensitivity of CLS by confining an ion bunch of rare isotopes in a multi reflection time of flight (MR-ToF) device. Hence, while the ions are bouncing back and forth between the electrostatic mirrors of the MR-ToF apparatus, the same ion bunch can be probed by the spectroscopy laser during each revolution. This increased observation time boosts the sensitivity by a factor of 30-600 compared to conventional CLS. At the same time, the high resolution of CLS on fast beams, which is approaching the natural line width, is maintained as MIRACLS' future MR-ToF device will be operated at unprecedented 30 keV.

This presentation will show recent results of a proof-of-principle experiment utilizing a low energy MR-ToF setup [3] which was modified for the purpose of CLS [4-6]. This allowed the successful experimental demonstration and systematic studies of the novel MIRACLS concept with ~1.5 keV ion beams of stable magnesium and calcium isotopes. Furthermore, progress of the development of the future 30 keV-device will be shown.

#### References

- [1] P. Campbell, I. Moore, M. Pearson, Progress in Particle and Nuclear Physics 2016, 86, 127-180.
- [2] R. Neugart et al., J. Phys. 2017, G44:6, 064002.
- [3] M. Rosenbusch et al., AIP Conference Proceedings 2013, 1521, 53-62.
- [4] F. Maier et al., Hyperfine interactions 2019, 240:54.
- [5] S. Sels et al., Nucl. Instrum. Methods Phys. Res. Section B 2019, 0168-583X.
- [6] S. Lechner et al., Hyperfine Interactions 2019, 240:95.

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## Workshop Photo

Poster Session / 51

### Gamma and fast-timing spectroscopy of the doubly-magic nucleus Sn-132

**Authors:** Jaime Benito<sup>1</sup>; Luis Fraile<sup>1</sup>; Agnieszka Korgul<sup>2</sup>; Monika Piersa<sup>2</sup>

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During the last decades there has been a substantial effort to obtain information about the region around the neutron-rich  $^{132}\text{Sn}$ , the most exotic doubly-magic nucleus presently at reach. The isotope  $^{132}\text{Sn}$  is itself a very interesting case. The simplest excited levels correspond to particle-hole states where a particle is excited across the energy gap of the neutron or proton closed shell. The identification of the multiplets may provide information on the nuclear two-body matrix elements.

In this contribution we report on the fast-timing and gamma spectroscopy of  $^{132}\text{Sn}$  carried out in the framework of the ISOLDE IS610 experiment. The excited states of Sn isotopes were populated in the beta-decay of In isomers, produced in a  $\text{UC}_x$  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 of indium. 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 of two  $\text{LaBr}_3(\text{Ce})$  detectors and a fast beta detector. The setup incorporated a tape transport system to remove longer-lived activities.

Here we concentrate on the excited structure of  $^{132}\text{Sn}$ , populated in the  $\beta$ -decay of  $^{132}\text{In}$ , and also, owing to the RILIS isomer selectivity, separately from the  $\beta$ -n decay of the  $^{133}\text{In}$   $1/2^-$  isomer and  $^{133}\text{In}$   $9/2^+$  the ground state. We present results of the analysis that include an expanded level-scheme, which more than a dozen new levels and more than 40 new  $\gamma$ -transitions. These results are completed with new measurements of the lifetimes of  $^{132}\text{Sn}$  excited states.

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## Feasibility of recoil distance lifetime measurements using transfer reactions at T-REX/ISS

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The Recoil Distance Doppler-Shift (RDDS) technique [1] has become a well established method of measuring the lifetimes of excited nuclear states. A two-foil plunger allows excited nuclei to radiate either one of two velocities. This results in two  $\gamma$ -ray energies associated with each transition due to the Doppler shift in energy. The relative intensity of each of these components can then be used to calculate the lifetime of the state. Such devices typically use fusion evaporation reactions to produce the nuclei of interest.

The feasibility of a plunger device that would allow for RDDS lifetime measurements to be made in conjunction with transfer reactions within T-REX or ISS is investigated. This would allow for selection on beam-like and recoil-like events. A similar plunger device is already used with the CLARA and PRISMA spectrometers [2] that allows for lifetimes to be probed using transfer reactions. Performing transfer reactions with a plunger would allow for model independent measurement of transition rates between excited nuclear states in neutron rich nuclei. Transition rates currently obtained from such reactions at ISOLDE are dependent on the choice of optical model used, as they are calculated from the deduced wavefunctions of the nuclear states.

The ability to perform transfer reactions in conjunction with a plunger device would allow for lifetimes of excited nuclear states within neutron rich nuclei to be probed. Examples of lifetime measurements that would be a motivation for developing such a device are also presented.

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## Poster Session / 1

## Structure of beta-decay strength function and quenching of axial-vector weak interaction constant $g(A)$ in halo nuclei and in some neutron rich nuclei

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The information on how the nuclear structure effects the beta-decay or charge-exchange reactions is most conveniently expressed by a strength function. The beta-decay probability is proportional to the product of the lepton part described by the Fermi function and the nucleon part described by beta-decay strength function. Beta-decay strength function reflects the distribution of the squared beta-decay matrix elements with respect to the excitation energy of the nuclear states of the daughter nucleus [1,2].

In the case of precise Wigner's SU(4)symmetry Isobar Analog Resonance (IAR) and Gamow-Teller Resonance(GTR) energies are degenerate and we may expect that  $E(\text{IAR}) = E(\text{GTR})$ . From our estimation follows [3] that the value  $Z/N = 0.6$  corresponds to the SU(4) region. The quenching of  $g(A)$  can be observed in GT beta-decay of halo nuclei and of some neutron rich nuclei, where  $E(\text{GTR}) < E(\text{IAR})$  [4] and GTR (or low-energy super Gamow-Teller phonon [5]) may be observed. Method of  $g(A)$  determination by comparison of experimental value of total beta-decay strength for GT beta-transitions with the Ikeda sum rule is the model-independent method and it may be applied for some halo nuclei and neutron rich nuclei [4].

Possible experiments on beta-decay strength function study in halo and in neutron rich nuclei are discussed.

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[5] Y. Fujita et al, Phys. Rev. C **91**, 064316 (2015)

## Poster Session / 49

## On the Shape of $^{20}\text{Ne}$ : Solution to Long-Standing Nuclear Conundrum

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The spectroscopic quadrupole moment of the first excited  $2_1^+$  state,  $Q_s(2_1^+)$ , at 1.633 MeV in  $^{20}\text{Ne}$  has been determined from reorientation effect Coulomb-excitation measurements at safe energies using the {small AFRODITE} array at iThemba LABS. A diagonal matrix element of  $\langle 2_1^+ || \hat{E}2 || 2_1^+ \rangle = -0.34(5)$  eb yields a large value of  $Q_s(2_1^+) = -0.26(4)$  eb, which presents strong discrepancies when compared with cluster-model and mean-field calculations, which underestimate it by at least 30%, and is in disagreement by  $3\sigma$  with the collective model of Bohr and Mottelson. Nevertheless, a slightly larger nuclear polarizability than the one assumed in previous work resolves this 45-year old conundrum between Coulomb-excitation measurements versus nuclear theory and the collective model.

**Poster Session / 48****Search for new and old magic numbers****Authors:** Cebo Ngwetsheni<sup>1</sup>; Jose Nicolas Orce Gonzalez<sup>1</sup><sup>1</sup> *University of the Western Cape (ZA)***Corresponding Author:** cebo.ngwetsheni@cern.ch

The nuclear dipole polarizability is mainly governed by the dynamics of the giant dipole resonance and, assuming validity of the Brink-Axel hypothesis, has been investigated along with the effects of the low-energy enhancement of the photon strength function for nuclides in medium- and heavy-mass nuclei. Cubic-spline fits to both data sets extrapolated down to a gamma-ray energy of 0.1 MeV show a significant reduction of the nuclear dipole polarizability for semi-magic nuclei, with magic numbers  $N = 28, 50$  and  $82$ , which supports shell effects at high-excitation energies in the quasi-continuum region. This work assigns  $\sigma_{-2}$  values as sensitive measures of long-range correlations of the nuclear force and provides a new spectroscopic probe to search for old and new magic numbers at high-excitation energies.

**Poster Session / 47****Study of Shape Coexistence in  $^{82}\text{Sr}$** **Authors:** Senamile Masango<sup>1</sup>; Jose Nicolas Orce Gonzalez<sup>1</sup>; Jack Henderson<sup>2</sup>**Co-authors:** Greg Hackman<sup>3</sup>; Nikita Bernier<sup>3</sup>; K. Abrahams<sup>4</sup>; Cebo Ngwetsheni<sup>1</sup><sup>1</sup> *University of the Western Cape (ZA)*<sup>2</sup> *University of York (GB)*<sup>3</sup> *TRIUMF*<sup>4</sup> *University of the Western Cape***Corresponding Author:** senamile.masango@cern.ch

The nucleus  $^{82}\text{Sr}$  lies in a transitional region of the nuclear landscape, between  $N=50$  spherical nuclei and the highly-deformed  $N \leq 40$  region. The ratio of  $B(E2; 4+ \rightarrow 2+)/B(E2; 2+ \rightarrow 0+)$  deviates heavily from systematics at  $^{82}\text{Sr}$  which could indicate additional physics at relatively low excitation energy. Shape effects in  $^{82}\text{Sr}$  have been investigated through the safe multi-step Coulomb excitation using the TIGRESS array at TRIUMF, with the intention of measuring the  $B(E2)$  and  $Q_s$  values, in particular  $Q_s(2+)$  and  $Q_s(41)$ . The model-independent Kumar-Cline sum rules will be used to establish the deformation in the intrinsic frame of the nucleus, allowing for the identification of phenomena such as shape coexistence. The extraction of transitional and diagonal matrix elements using GOSIA will probe the possibilities of shape coexistence and triaxial shapes. For background reduction, the particle-gamma coincidence technique has been used with TIGRESS and a double-sided silicon detector.

**Poster Session / 46****Combined Density Functional Theory and Perturbed Angular Correlation study of  $\text{SrMnGe}_2\text{O}_6$ ,  $\text{SrCoGe}_2\text{O}_6$  and  $\text{CaMnGe}_2\text{O}_6$** **Authors:** Araujo Joao Pedro Esteves De Araujo<sup>1</sup>; Armandina Maria Lima Lopes<sup>1</sup>; Céline Darie<sup>2</sup>; Céline Goujon<sup>3</sup>; Claire Colin<sup>2</sup>; Goncalo De Pinho Oliveira<sup>1</sup>; Joao Martins Correia<sup>4</sup>; Lei Ding<sup>5</sup>; Muriel Legendre<sup>2</sup>; Pedro Miguel Da Rocha Rodrigues<sup>1</sup>; Ricardo Manuel Alves Pacheco Moreira<sup>1</sup>; Tiago Leal<sup>6</sup>

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Multiferroic materials have been under the spotlight due to their fundamental scientific interest and for potential applications in technology. Among these interesting materials are the group of compounds belonging to the Pyroxene family with general chemical formula  $AM(Si,Ge)_2O_6$ . More specifically,  $SrMnGe_2O_6$ ,  $SrCoGe_2O_6$  and  $CaMnGe_2O_6$  are isostructural, crystallizing with monoclinic  $C2/c$  symmetry and are characterized by zigzag chains of  $MnO_6$  octahedra linked by edge-sharing, separated by  $GeO_4$  tetrahedra chains along the same axis, linked by corner-sharing. Due to this arrangement these systems present a rich diversity of low-dimensional magnetic properties. The existence and possible interplay of low dimensionality and magnetic frustration results in multiferroic and/or magnetoelectric properties.

Since these properties might arise from local structural features that are not well described by methods based on long-range average structural models, the use of local probe studies is essential. In this context, hyperfine methods, such as perturbed angular correlation (PAC) spectroscopy where the study of the electric field gradient (EFG) in the vicinity of a probe atom, allows reconstructing of the atomic and electronic environment of the probe in the material, helps to clarify the origin of the properties exhibited in these systems. In this work a temperature dependent EFG study will be presented and discussed, guided by EFG simulation results using ab-initio WIEN2k, attempting to clarify the experimental observations in these compounds.

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**Poster Session / 41**

## Towards a beta spectrum shape measurement at WISArD

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There are indications that the measured number of antineutrinos emerging from reactor fission fragments inside a reactor is lower than theoretically predicted. Moreover, there is an additional anomaly in the energy spectrum of the antineutrinos. These observations are the reactor neutrino anomaly. One of the uncertainties in the theoretical description is the QCD influence on the  $\beta$ -decay of which the weak-magnetism term is the major contribution. Its value is unknown experimentally in the mass range of the reactor fission fragments. [1] A direct measurement is possible with the beta energy spectrum and would be the first of its kind in this mass range. In addition, the performed fit can include the Fierz interference term to probe beyond standard model (BSM) physics, i.e. weak tensor or scalar currents. BSM experiments aim for a precision close to  $10^{-3}$  and, thus, complementarity to high energy experiments, e.g. LHC, within an effective field theory. [2]

Spectrum shapes were measured extensively in the past but only recently attracted renewed interest. The main sources of systematic uncertainties are energy losses in the source (foils), the detector dead layer and the rather high backscattering probability for electrons. Using the progress in Monte Carlo simulation (e.g. Geant4) over the last couple of years it is possible to improve on previous results. [2]

During the long shutdown at CERN we will adapt the existing WISArD set-up at CERN with the objective to measure the beta-spectrum shape of  $(^{114}\text{In})$ , a pure Gamow-Teller decay. With two energy detectors along a high magnetic field the set-up has a full solid angle. Moreover, backscattered particles are not lost but spiral towards the other detector. Using Geant4 a feasibility study is completed and first data taking is planned in short notice thus preliminary results might be shown. [1] A. C. Hayes and P. Vogel. Reactor neutrino spectra. Annual Review of Nuclear and Particle Science, 66(1):219–244, 2016.

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Poster Session / 39

## Laser spectroscopy on germanium isotopes at COLLAPS-CERN

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Collinear laser spectroscopy (CLS) is a high-precision technique to study the hyperfine structure (HFS) of atoms and ions [1]. The hyperfine constants are observables that contain atomic and nuclear information simultaneously. While the atomic part is independent of the neutron-number in

isotopes of the same element, the contribution of the nuclear part is different due to the different nuclear properties of the isotopes in the studied element. This allows to extract in a nuclear-model independent way a consistent set of nuclear moments along an isotopic chain.

The hyperfine spectra of  $^{68-74}\text{Ge}$  ( $Z = 32$ ) were acquired at the COLLAPS experimental setup located at ISOLDE-CERN. With the use of the frequency mixing technique, we have been able, for the first time at COLLAPS, to produce 269nm continuous wave (CW) laser light to study the  $4s^2 4p^2 \ ^3P_1 - 4s^2 4p 5s \ ^3P_1$  atomic transition. From the hyperfine constants of the  $^{69,71,73}\text{Ge}$  isotopes, measured across the isotopic chain, the nuclear electromagnetic moments are deduced. Those of  $^{71,73}\text{Ge}$  are found to be consistent with the earlier observed values [2,3,4], while the nuclear magnetic and quadrupole moments of  $^{69}\text{Ge}$  are significantly different [5]. In this contribution, the new results are presented and compared to shell model calculations.

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#### Poster Session / 37

### Reestablishing the photoluminescence lab at ISOLDE: Is there a link between photoluminescence and emission channeling?

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Photoluminescence (PL) is an optical, non-destructive technique that is often used to characterize the defects in semiconductors. However, the proper chemical identification for the origin of signals can be misleading. Implanting samples with radioactive probes at ISOLDE allows for a clear chemical classification of a peak in a PL spectrum as its intensity changes with time. In this work we present the reestablishment of a PL setup at ISOLDE and progress towards its thorough testing.

The setup consists of three main components a HeCd laser for excitation of the sample, a cryostat, where the sample was mounted and a spectrometer to which two detectors were attached, a CCD (for the visible range) and an InGaAs (for the infrared range). Some miscellaneous optical components were also used to redirect and focus the beam. Multiple mounting methods of the samples were also tested.

The samples studied were mainly of GaN, with different doping characteristics, and diamond. Some of the samples were previously used in emission channeling (EC) experiments allowing for a simultaneous search for a link/correlation between PL, a global technique, and EC, a local technique. From the PL spectra of the n-GaN:Si sample, recorded at multiple positions, it was possible to see that the doping had changed to almost intrinsic in its middle but not in the other positions. The change is due to the implantation of stable Mg in this sample during EC experiments. As the implantation concentration of stable Mg was approximately equal to the initial concentration of Si on the sample, for the behavior to become intrinsic most of the implanted Mg had to be in its active location on the lattice, the substitutional position. This is in agreement with the EC experiments completed on this sample, which found that approximately 95% of the 27Mg implanted was substitutional in n-GaN:Si. Besides the link found between EC and PL, the work has led to a fully functional PL setup at the ISOLDE facility. Python scripts have also been developed which automate part of the measuring and analysis processes.

#### Poster Session / 36

### Masses of $^{70}\text{As}$ , $^{49,50}\text{Sc}$ and $^{73}\text{Br}$ isotopes

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Atomic masses provide direct insights on key nuclear structure phenomena, such as shell effects or onsets of deformation, and the way they evolve far from stability. In the field of astrophysics, the masses of exotic species constitute one of the most critical nuclear physics inputs in nucleosynthesis calculations.

The ISOLTRAP, located at the radioactive ion-beam facility ISOLDE/CERN [1], pioneered the on-line Penning-trap mass spectrometry of unstable isotopes. During its thirty years of operation, over 400 nuclides have been measured. With the well-established Time-of-Flight Ion Cyclotron-Resonance (ToF-ICR) technique the achievable relative uncertainty is on the level of  $10^{-8}$ . To improve the ISOLTRAP's ability to deliver purified beams to the measurement Penning trap, a Multi-Reflection Time-of-Flight Mass Separator (MR-ToF MS) has been constructed [2]. This device is routinely used as mass spectrometer on its own. This contribution will present the principles of both mass measurement techniques through recent investigations of <sup>70</sup>As, <sup>49,50</sup>Sc and <sup>73</sup>Br isotopes.

To push such investigations towards more exotic and rare radioisotopes the efficient transportation, collection, accumulation and cooling of the beam is required. To this end, radio-frequency cooler and buncher (RFQ-CB) devices have become the tool of choice [3]. This poster will highlight recent technical developments laying the groundwork for the overall improvement of RFQ-CB and the alignment of ISOLTRAP's horizontal beam line.

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## Poster Session / 31

### The electronic structure calculations of Fe doped monolayer MoS<sub>2</sub> using density functional theory

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Recently, the single-layer two-dimensional (2D) of MoS<sub>2</sub> is an important transition metal dichalcogenides (TMDs) compound which has been investigated [1,2]. Similar to the graphene, the monolayer of MoS<sub>2</sub> is used in a wide range of application including field-effect transistors, photodetectors, solar cells, chemical sensors and supercapacitors electrodes [3,4]. Furthermore, due to the relatively high direct band gap of 1.8 eV in the monolayer MoS<sub>2</sub>, it has great advantage respect to the graphene that can be used as a host material for transition metal implantation.

In this work, the magnetic and electronic properties of monolayer MoS<sub>2</sub> doped with Fe atoms have been investigated by first-principle calculations in the framework of density functional theory (DFT) based on the full-potential linear augmented plane wave (FP-LAPW) method as implemented in the wien2k code [5]. The various configurations of Fe doped MoS<sub>2</sub> (*I.* Substitutional Fe doped Mo site, *II.* Substitutional Fe doped Mo site with vacancies of S atom, *III.* Interstitial Fe on the surface of monolayer MoS<sub>2</sub>) have been stimulated. The charge state of Fe and the density of states of each configurations are discussed.

The results of this work provide information about the change of the electronic structure in the monolayer MoS<sub>2</sub> with different implanted Fe site.

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**Poster Session / 29**

## **GammaMRI: towards high-resolution single photon imaging using highly-polarized gamma-emitting nuclei**

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A new hybrid medical imaging modality with promising benefits for in vivo studies has been under development since 2017 by the CERN-UCM-UNIGE and HEdS-Geneva collaboration. With this technique, called gammaMRI, we are aiming to combine the high spatial resolution of MRI (~1 mm) while increasing the sensitivity of the technique using radioactive tracers as contrast agents, as performed in PET and SPECT [1,2]. In addition, we can possibly profit from the clinical benefits of xenon isotopes [3].

The gammaMRI setup has been assembled and tested over the timespan of the last two years. This technique is based on the detection of asymmetric  $\gamma$ -ray emission of long-lived polarized nuclear states in the presence of low magnetic fields (4.5 mT) [2]. The nuclei used in our proof-of-principle experiments are the long-lived isomers of Xe isotopes:  $^{129m}\text{Xe}$  ( $T_{1/2} = 8.9$  d),  $^{131m}\text{Xe}$  ( $T_{1/2} = 11.8$  d) and  $^{133m}\text{Xe}$  ( $T_{1/2} = 2.18$  d) produced at the ILL high flux reactor in Grenoble and at the ISOLDE facility at CERN [4].

The two established methods of Xe production required different extraction techniques of these isotopes. Due to the gaseous state of the radioactivity used, special handling and radiation protection procedures were followed. The production of  $^{133m}\text{Xe}$  was tested at GLM (General Low Mass) end station at ISOLDE. Satisfying yields of  $^{133m}\text{Xe}$  (80 –270 MBq) were obtained from thorium carbide (ThC) and uranium carbide (UCx) targets. During LS2  $^{129m}\text{Xe}$  (300 MBq) and  $^{131m}\text{Xe}$  (100 MBq) isotopes were produced at ILL by irradiating stable Xe atoms with thermal neutrons. During the experimental period of 2019, the finalised polarisation setup was tested under working conditions. Different parameters contributing to polarisation efficiency of xenon were tested: partial pressure of Xe and N<sub>2</sub>, gas mixture temperatures, Rb vapor saturation, glass cell shapes and the internal wall coating for nuclear spin relaxation etc. This contribution will present the principle of gammaMRI and the results of the tests performed this summer.

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**Poster Session / 28**

## Investigation of the low-energy isomer $^{229m}\text{Th}$ using the beta decay of $^{229}\text{Ac}$

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A unique feature of thorium-229 is its isomer with an exceptionally low excitation energy, proposed as a candidate for future optical clocks [1]. The small decay width is expected to outperform the accuracy of current state-of-the-art atomic clocks by an order of magnitude [2]. The current best measurement of the excitation energy results in a value of 8.28(17)eV [3], whereby the isomer is populated in the alpha decay of uranium-233. The development of such a clock requires however a precision on the order of 10meV. Spectroscopic experiments searching for a direct signature of the gamma decay have to-date been unsuccessful due to the background induced in the population process of the isomer.

A new approach using the beta decay of actinium-229 is studied as a novel production method to populate the isomer with high efficiency and in low background conditions. Produced online at the ISOLDE facility, actinium is laser-ionized and implanted into a suitable crystal. Results from an experiment investigating the production of actinium and the feeding of the daughter's isomer in its beta decay are presented. Using this method, a higher isomer population yield and better background control are expected to make the vacuum-ultraviolet spectroscopy of the radiative decay and the precise determination of the isomer's excitation energy feasible.

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## Poster Session / 21

### Contribution of sources of P,T-violation to permanent electric dipole moments of molecules

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“New physics” beyond the standard model, such as supersymmetric models, can imply violations of discrete symmetries, i.e. space parity (P), time-reversal (T) and charge conjugation (C). Many different hypothetical sources of simultaneous violation of P- and T-symmetry can be discussed on the elementary particle level, such as P,T-odd currents between quarks and electrons or permanent electric dipole moments (EDMs) of elementary particles. All these fundamental P,T-odd interactions could induce net P,T-odd moments in bound systems such as atoms and molecules[1]. Thus, a measurement of e.g. a permanent EDM of an atom or a molecule is difficult to interpret and predict due to possible interference of the various fundamental sources of P,T-violation. Nonetheless, due to enormous electronic structure enhancements of such P,T-odd effects in polar molecules, low-energy high-precision experiments on these molecules can give access to the TeV energy-regime[2, 3].

In this poster possible sources of discrete symmetry violation are summarised and their effects on molecular spectra are discussed. Requirements of molecules for high-precision spectroscopy that aims to measure a permanent molecular EDM are elucidated. Trends of P,T-violation within the periodic table of elements determined with quasi-relativistic calculations[4, 5] as well as measurement models for disentanglement of sources of P,T-violation in molecules are discussed[6, 7]. Simple analytical models, which are gauged by ab initio calculations, help to identify suitable molecules for experiments.

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## Poster Session / 19

## The PUMA experiment at CERN/ISOLDE

Frank Wienholtz for the PUMA Collaboration

The PUMA experiment aims to use antiprotons as a tool for exploring the properties of exotic nuclei by probing the distribution of the protons and the neutrons on the surface of the nucleus. To be able to do this, a mobile Penning-trap system must be designed and built which will allow to transport antiprotons from CERNs antiproton decelerator (AD) facility to the ISOLDE experimental hall. This contribution will detail the general concept of the PUMA experimental setup, it will present its mayor physics goals and detail the feasibility within the current experimental infrastructure at ISOLDE.

Poster Session / 18

### Ultrasensitive $\beta$ -NMR in chemistry

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The  $\beta$ -detected NMR technique is a well-described nuclear spectroscopy technique known to give signals with up to ten orders of magnitude more sensitive than conventional NMR. This is achieved by combining the hyperpolarization of the radioactive nuclear spins with lasers and the detection of the emitted beta particles. An additional advantage of the  $\beta$ -NMR is the ability to perform the real-time investigation of chemical reactions, such as biomolecular folding processes and catalytical mechanisms.

Herein, we demonstrate the basic principles of our technique, experimental setup and detailed data analysis. We will focus on the results obtained in 2018 (chemical shifts and T1 relaxation times) supported by conventional <sup>1</sup>H and <sup>23</sup>Na NMR results explaining the <sup>26</sup>Na dynamics in liquid hosts such as ionic liquids. Additionally, we will complement our conclusions with quantum mechanical computations.

Poster Session / 13

## Study of octupole collectivity in $^{146}\text{Nd}$ and $^{148}\text{S}$

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For certain combination of protons and neutrons an appearance of reflection asymmetry is expected. In particular, the experimentally determined E3 strengths as a function of the neutron number are peaked around  $N=88$  and  $N=134$ . Many theoretical approaches have been applied to describe the regions of enhanced octupole collectivity and its experimental signatures, such as parity doublets in odd-mass nuclei, and low-lying opposite-parity bands and high E3 transition probabilities in even-even nuclei.

Low-energy Coulomb excitation is a highly successful method for establishing the evolution of nuclear shapes via measurements of cross sections to populate excited states that can be directly related to the static and dynamic moments of the charge distribution of the nucleus.

The octupole correlations in the  $^{146}\text{Nd}$  ( $N=86$ ,  $Z=60$ ) and  $^{148}\text{Sm}$  ( $N=86$ ,  $Z=62$ ) nuclei were investigated in a Coulomb excitation experiment with stable  $^{58}\text{Ni}$  and  $^{32}\text{S}$  beams. The experiment was part of the MINORCA Campaign (MINIBALL spectrometer coupled with ORGAM Array) at IPN Orsay.

We present the status of data analysis from this experiment with a particular focus on the  $\langle 3^- || E3 || 0^+ \rangle$  and  $\langle 1^- || E3 || 4^+ \rangle$  matrix elements that are expected to provide a distinction between an octupole vibration and a rigid deformation.

**Poster Session / 61**

## Development of offline ISOL test facilities at SCK•CEN

**Authors:** Alex Denisov<sup>1</sup>; Donald Houngho<sup>1</sup>; Jarno Van de Walle<sup>1</sup>; Joao Pedro Ramos<sup>1</sup>; Johny Mols<sup>1</sup>; Joris Van Eindhoven<sup>1</sup>; Kim Rijpstra<sup>1</sup>; Lucia Popescu<sup>1</sup>; Ludo Vermeeren<sup>1</sup>; Marc Dierckx<sup>1</sup>; Philip Creemers<sup>1</sup>

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In order to support the design of the first phase of ISOL@MYRRHA, which will operate with 100-MeV protons at intensities up to 500  $\mu\text{A}$ , SCK•CEN is currently developing offline facilities, including a thermal test stand and an ISOL system coupled to a laser laboratory. The aim is to develop a Target Ion Source Assembly, targets and ion sources that can properly use the aforementioned proton beam, but also to evaluate design decisions concerning beam optics and diagnostics, laser beam transport and remote handling.

The thermal test stand with a first conceptual TISA vacuum vessel has been completed and will soon test a first target container design. The ISOL setup and the laser laboratory will be realized in the coming two years. In this contribution we want to introduce these facilities and some of the design aspects.

**Ground state properties / 26**

## Molecules at ISOLDE: New Opportunities for Research on Nuclear Structure and Physics Beyond the Standard Model

**Author:** Robert Berger<sup>1</sup>

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In this talk I will review latest activities in molecular approaches to physics beyond the standard model and discuss challenges and opportunities that laser spectroscopy of specifically tailored heavy molecules provides. I plan to discuss: Synthesis of molecules with shortlived isotopes from spallation sources, laser cooling of radioactive molecules, measurement of nuclear anapole moments and neutron skins as well as detection of P,T-odd moments such as the electric dipole moment of the electron or nuclear magnetic quadrupole moments.

**Ground state properties / 20**

### The nuclear chart from nuclear forces

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In this talk, we will discuss ab initio calculations of the nuclear chart and predictions for the drip lines from light through medium-mass nuclei. Starting from a chiral two- and three-nucleon interaction with good saturation properties, we have calculated ground-state and separation energies for all nuclei from helium to iron, nearly 700 in total. From a systematic comparison, we find that the deviation of separation energies from experiment yields an approximately Gaussian distribution. We use this to provide theoretical uncertainties for our ab initio calculations towards the drip lines. Where the drip lines are known experimentally, our predictions are consistent within the estimated uncertainty. For the neutron-rich fluorine to titanium isotopes, we provide predictions to be tested at rare-isotope beam facilities. This work demonstrates that ab initio calculations are advancing to global theories. In addition, we will highlight applications of ab initio calculations to ISOLDE experiments and discuss new directions in the development of nuclear forces and electroweak interactions in nuclei.

**Ground state properties / 35**

### Binding energy studies of shell closures in exotic nuclei with ISOLTRAP

**Authors:** Maxime Jean Albert Mougeot<sup>1</sup>; Pauline Ascher<sup>2</sup>; Dinko Atanasov<sup>1</sup>; Klaus Blaum<sup>3</sup>; burcu Cakirli<sup>4</sup>; Thomas Elias Cocolios<sup>5</sup>; Sergey Eliseev<sup>6</sup>; Sebastian George<sup>7</sup>; Frank HERFURTH<sup>None</sup>; Alexander Herlert<sup>8</sup>; Wenjia Huang<sup>9</sup>; Yuri Litvinov<sup>10</sup>; Jonas Kartheim<sup>11</sup>; Ivan Kulikov<sup>12</sup>; David Lunney<sup>13</sup>; Vladimir Manea<sup>14</sup>; Dennis Neidherr<sup>12</sup>; Lutz Christian Schweikhard<sup>15</sup>; Timo Pascal Steinsberger<sup>16</sup>; Andree Welker<sup>17</sup>; Frank Wienholtz<sup>1</sup>; Robert Wolf<sup>8</sup>; Kai Zuber<sup>18</sup>

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One modern approach to unravelling the complex nuclear many body problem has been to track the evolution of nuclear properties in systems ever closer to the proton or neutron drip-line. Binding energies are among the first observables reaching yet uncharted regions of the nuclear chart and their trends are sensitive to a wide range of nuclear-structure phenomena. As such, they provide invaluable inputs to virtually all nuclear models.

In this contribution, results from two mass measurement campaigns performed with the ISOLTRAP high-precision mass spectrometer [1-2] located at ISOLDE/CERN will be presented. The first such campaign was dedicated to the study of the  $N=28$  shell closure in the argon isotopic south of the doubly-magic  $^{48}\text{Ca}$ . The experimental binding energy trends obtained from the precisely determined masses of  $^{46-48}\text{Ar}$  will be compared to predictions from state-of-the-art ab-initio calculations.

Another recent experiment was dedicated to the study of neutron-deficient indium isotopes in the vicinity of the doubly-magic  $^{100}\text{Sn}$ . This campaign performed at the extreme of the nuclear landscape was successful in measuring  $^{99-101}\text{In}$ . Thanks to the recently commissioned Phase-Imaging Ion-Cyclotron-Resonance technique [3], the mass of a long lived isomeric state in  $^{101}\text{In}$  could also be determined. Implications of the newly measured masses for the  $Z=N=50$  shell closure in close proximity with the proton drip-line as well as for the astrophysical  $rp$ -process will be highlighted.

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## Ground state properties / 44

### Investigating the large nuclear charge radii around $N = 32$

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The exotic isotopes in the Ca region ( $Z = 20$ ) have attracted significant experimental and theoretical attention due to the proposed shell closures at neutron numbers  $N = 32, 34$  [1-5]. In particular, the subshell closure at  $N = 32$  represents a puzzling case, since the unexpectedly large charge radius of  $^{52}\text{Ca}$  [2] challenges the magicity of this isotope. The lack of a consistent theoretical explanation behind the mechanism driving the evolution of the charge radii in this region of the nuclear chart continues to motivate theoretical and experimental advances.

The hyperfine structure of  $^{52}\text{K}$  ( $N = 33$ ) was measured with the Collinear Resonance Ionization Spectroscopy (CRIS) technique [6]. This work demonstrates for the first time the combination of the CRIS method with beta-detection, paving the way for future measurements on radioactive beams that are heavily contaminated with stable or long lived isotopes. Our result represents the first measurement of a charge radius beyond  $N = 32$  in the Ca region, allowing us to investigate if the stabilizing effect of a shell closure is present at this proposed magic number.

The experimental results are furthermore compared to state-of-the-art coupled cluster and energy density functional calculations with the aim to explore the mechanisms behind the large charge radii of isotopes in this region.

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- [5] Miller, A.J, et al., Nature Physics 15, 432-436 (2019).
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**Ground state properties / 3****Exploring the antimony (Z=51) isotopic chain with laser spectroscopy****Author:** Simon Lechner<sup>1</sup>

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Antimony (Sb) contains 51 protons, one proton above the magic  $Z = 50$  proton shell closure. Therefore, its magnetic moments serve as an ideal candidate to probe the proton single particle behavior along the Sb isotopic chain, while its quadrupole moments shed light on collectivity and core polarization effects as a function of neutron number towards the shell closure at  $N = 82$ . Furthermore, the change in charge radii across  $N = 82$  can provide a stringent test on nuclear structure theories. For instance, the recent result from the Sn isotopes clearly prefers density function theory of Fayans type over the conventional Skyrme functional [1]. It is therefore of great interest to investigate the influence on the nuclear charge radii from the single proton outside the  $Z = 50$  core.

So far, only scarce data on Sb is available in literature, especially on quadrupole moments and charge radii [2]. Hence, at the COLLAPS experimental beam line (ISOLDE-CERN), hyperfine spectra of 112-134Sb ( $N = 61 - 83$ ), including many isomers, were measured by the means of high-resolution collinear laser spectroscopy [3] for the first time using the atomic transition  $5s25p3\ 4S3/2 \rightarrow 5s25p26s\ 4P3/2$  (transition wavelength 217 nm). From the obtained hyperfine structure nuclear observables such as nuclear spins, magnetic dipole moments, electric quadrupole moments and charge radii are extracted.

This contribution will present these results, providing new insights into the nuclear structure in this mass region and pinning down the nuclear spins of several isotopes, which are currently only tentatively assigned [4]. Additionally, shell-model calculations within the 50-82 major shell (for both proton and neutron) are compared to the trend of the quadrupole moments.

## Ground state properties / 45

### Determination of the magnetic moments of 26–30Na isotopes with part-per-million precision

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As a result of our continuing quest to apply  $\beta$ -NMR to biomolecular and chemical studies, we report here the measurement of the magnetic moment of  $^{26}\text{Na}$  with a few ppm precision. This also led to an improved precision on the magnetic moments of  $^{27-30}\text{Na}$ . This achievement was made possible by the previously reported 2018 upgrades to the  $\beta$ -NMR setup [IsoWork18], which resulted in an improvement in the long-term stability and homogeneity of the magnetic field to ppm level and decreased the sample replacement time. The use of a suitable liquid host compatible with the vacuum environment of  $\beta$ -NMR experiments. New *ab initio* calculations of the NMR shielding constants of sodium and conventional NMR reference measurements of  $^1\text{H}$  and  $^{23}\text{Na}$ . The results connect the NMR frequencies of short-lived Na isotopes to that of stable nuclei, paving the way for their use in biochemical applications, where ppm precision is important to determine the chemical environment. Furthermore, this approach can be applied to other isotopic chains, which can open the way for many other applications of  $\beta$ -NMR in biochemical research, nuclear-structure studies or fundamental research.

[IsoWork18] J.Croese et. al, ISOLDE Workshop and Users meeting 2018, Poster 38

**Technical session / 52**

## Post-LS2 RILIS Capabilities

**Authors:** Shane Wilkins<sup>1</sup>; Bruce Marsh<sup>1</sup>; Katerina Chrysalidis<sup>2</sup>; Valentine Fedosseev<sup>1</sup>; Edu Granados<sup>1</sup>; Dmitry Fedorov<sup>3</sup>; Pavel Molkanov<sup>3</sup>; Maxim Seliverstov<sup>3</sup>

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Numerous avenues of development are being pursued to expand the capabilities of the Resonance Ionization Laser Ion Source (RILIS) beyond the CERN Long Shutdown 2. To improve the reach of the solid-state laser system and offer greater flexibility during ionization scheme development, promising progress in the extending of the spectral range of the existing titanium-sapphire lasers through stimulated Raman scattering has been made [1]. Results of a prototype cavity that allows for efficient generation of broadband light in the blue-green region, without relying upon UV-pumped dye lasers, will be presented. A new beam observation system has been designed so that laser beams can be positionally stabilized within both the HRS and GPS ion sources simultaneously. This will reduce a common bottleneck during on-line setups and in some cases even permit dual-separator operation. An exploratory study investigating the feasibility of fragmenting simple molecules using ultrashort laser pulses in realistic ion source conditions has been performed. The MELISSA laser laboratory was commissioned earlier in the year and has been in operation for the MEDICIS scientific program of 2019. A brief overview of this new laser ion source will be provided.

[1] K. Chrysalidis et al., Opt. Lett. 44, 3924-3927 (2019)

**Technical session / 17**

## HIE -ISOLDE capabilities after LS2

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This presentation will give you an overview of the Long Shutdown 2 work carried out on the REX and HIE ISOLDE post-accelerator. The repaired Cryo Module 4 which was taken out at the beginning of the year will come back to ISOLDE in 2020 with all five accelerating SRF cavities working. This will increase the total deliverable energy of the HIE ISOLDE Linac. An overview will be given of the expected available beam energies after LS2.

If green light from the CERN management is given we hope to perform not only the recommissioning of the NC REX and SC HIE ISOLDE post-accelerator in 2020 but also perform machine test and development runs to have a better understanding of the parameters and capabilities of the post-accelerator with the goal to optimize and improve setting-up times, beam quality and overall performance of the machine for the 2021 ISOLDE Physics run when the protons from the PS Booster become available. An overview of the plans for the 2020 recommissioning and test runs will be given during this presentation.

**Technical session / 16**

## Target and ion source developments

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The long shutdown 2 (LS2) of the CERN accelerator complex poses an ideal opportunity to focus on development and upgrade tasks.

Of particular interest are systematic studies for beam development that requires infrastructure and resources otherwise occupied or interrupted by target production. In this context, we have ramped up the investigation of molecular beams, where stabilizing the production of tin sulfide (SnS) beams was investigated first.

Other ongoing projects are optimization of target and ion source heating, process optimization for actinide carbide target production and re-oxidation, upgrade of the chemical lab for nano material development, integration of the LIST ion source, study for refractory beams and optimization of negative ion sources.

In this presentation, we will report on the status of the ongoing ISOLDE target, ion source and beam development and facility upgrades and an outlook will be given for the programme for the second half of LS2.

**Technical session / 25**

## Characterization of Ac, Ra and Fr beams at ISOLDE

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Over the past decades, ISOLDE has proven to be able to produce a big range of ion beams, spread over more than 70 different elements. However, ion beams of refractory or highly reactive elements are still very difficult to deliver. In particular, no beam of actinium has ever been investigated at ISOLDE. This is in part due to the expected poor release of this element and from how it may interact with the target material. However, thanks to recent developments in the resonant laser ionization scheme of Ac [1], the production of this difficult beam has become possible. The availability of this beam opens up new opportunities for its production via the ISOL method for fundamental research as well as for medical applications. Indeed, despite <sup>225</sup>Ac being a very promising isotope to be used in Targeted-Alpha-Therapy for the treatment of tumors, the production of this element is very difficult [2]. Therefore, the ISOL technique could play an important role in providing this isotope to hospitals, first for clinical research and then eventually for patient care.

In this contribution, I shall report on an experiment focusing on the production of the first Ac beams at ISOLDE (IS637) from A=214 to 231, as well as the beam characterization. Furthermore, Fr and Ra beams between A=205 and 231 were investigated and characterized and those results will be reported.

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## Workshop Dinner - Bois Joly Restaurant, Crozet

### Low-energy physics / 33

## Search for physics beyond the Standard Model with radioactive beams

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The search for physics beyond the standard electroweak model (SM), despite its remarkable success at the most elementary level, still continues on three frontiers - high-energy, precision and cosmic. The reason is the many yet unanswered questions such as the origin of parity violation [1].

Considering the precision frontier, experiments with radioactive nuclei offer large variety of nuclear states with optimal sensitivity to study the beta-neutrino angular correlation coefficient ( $a_{\beta\nu}$ ) that are still competitive to today's high-energy and cosmic experiments. In particular, studies performed in pure transitions, Fermi or Gamow-Teller provide a direct probe to the presence of scalar or tensor currents, respectively. Measurements of this kind have been performed in various nuclear systems in the past [2], with  $^{32}\text{Ar}$  being one of the most precisely known to date.

The experiment WISArD (Weak Interaction Studies with  $^{32}\text{Ar}$  Decay) [3] is currently being prepared at ISOLDE/CERN, and will focus on determining  $a_{\beta\nu}$  through beta-proton coincidence measurements. The ground state in  $^{32}\text{Ar}$  beta decays via the super-allowed Fermi transition to the isobaric analogue state in  $^{32}\text{Cl}$  which subsequently decays by proton emission. Measured kinematic shift of emitted protons reflects the energy spectrum of the recoiling nuclei after the previous beta-decay which depends on the character of the weak interaction. To enhance the measurement sensitivity emitted particles will be guided by a strong magnetic field. In this contribution the layout of the setup will be presented as well as preliminary results from a proof-of-principle campaign performed in the fall of 2018. Furthermore, a discussion about the potential precision at reach applying this technique will be given.

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**Low-energy physics / 32**

## Discovery of exceptionally strong electron-capture transition and consequences for the fate of intermediate-mass stars

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Stars of 7-11 solar masses are prevalent in the Galaxy, their birth and death rate comparable to that of all heavier stars combined. Yet, the ultimate fate of such "intermediate-mass stars" remains uncertain. According to current models a significant fraction explode, but the mechanism is a matter of ongoing debate. The answer – gravitational collapse or thermonuclear explosion – depends critically on the rate of electron capture on  $^{20}\text{Ne}$  in the stellar core. However, due to the unknown strength of the second-forbidden, non-unique transition between the ground states of  $^{20}\text{Ne}$  and  $^{20}\text{F}$ , it has not previously been possible to constrain this rate in the relevant temperature-density regime. In this contribution, we report the first measurement of this transition at the IGISOL facility of the Jyväskylä accelerator centre, provide the first accurate determination of the capture rate and explore the astrophysical implications. We find that the transition has an exceptionally large strength, in fact, the largest ever measured for a second-forbidden, non-unique transition. The transition enhances

the capture rate by several orders of magnitude, and we demonstrate that this has a decisive impact on the star's final evolution and ultimate fate.

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### Nuclear structure of odd-Au isotopes

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Excited state of odd-mass isotopes can be in general used as a probe of the structure of even-even cores. The odd particle or hole acts as a spectator and ordering and energies of excited states reveal information on, e.g., axial and triaxial deformation. In particular, excitation energy of low-spin states is very sensitive to triaxial parameter of the core. However, such states are usually not observed in in-beam studies, because of their non-yrast character. In the talk, the data for excited states of <sup>181,183</sup>Au will be presented. They were identified via  $\beta^+$ /EC decay of <sup>181,183</sup>Hg isotopes. Experiments were performed at ISOLDE using the TATRA tape system. High-resolution conversion electron data were collected and level schemes of both isotopes were constructed, including new electric monopole transitions. These level schemes allowed to study evolution of the triaxiality of even-even Hg isotopes. In addition to the data, general systematics of odd-Au isotopes will be presented.

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### $\beta$ -decay studies of neutron-rich indium isotopes: $\gamma$ -ray emission from neutron-unbound states in <sup>134</sup>Sn and <sup>133</sup>Sn

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Simple systems in the proximity of the doubly-magic shell closures constitute the best cases for testing the predictive power of shell-model calculations. In this context, understanding of the nuclear structure in the closest vicinity of the doubly-magic <sup>132</sup>Sn is essential before making extrapolations of the nuclear properties towards more neutron-rich nuclei. Recently, it was indicated that in the region southeast of <sup>132</sup>Sn nuclear structure effects affect the neutron versus  $\gamma$  ray competition in the decay of neutron-unbound states [1].  $\beta$ -decay studies of neutron-rich indium isotopes, <sup>135</sup>In, <sup>134</sup>In and <sup>133</sup>In, provide excellent conditions to investigate such effects since their decays are characterized by large energy windows for the population of neutron-unbound states ( $Q_{\beta n} > 10$  MeV). Consequently, states in  $\beta$ ,  $\beta n$  and even  $\beta 2n$  daughters of indium isotopes can be investigated simultaneously. These nuclei and the  $n$ - $\gamma$  competition following their  $\beta$  decay are also relevant in the framework of the astrophysical r-process since <sup>135</sup>In is a so-called waiting point [2].

Excited states in <sup>135</sup>Sn, <sup>134</sup>Sn, <sup>133</sup>Sn and <sup>132</sup>Sn were investigated via  $\beta$  decay of <sup>135</sup>In, <sup>134</sup>In and <sup>133</sup>In at ISOLDE Decay Station. Isomer-selective ionization using the Resonance Ionization Laser Ion Source enabled the  $\beta$  decays of <sup>133g</sup>In ( $I^\pi=9/2^+$ ) and <sup>133m</sup>In ( $I^\pi=1/2^-$ ) to be studied independently

for the first time [3]. Owing to the large spin difference of those two  $\beta$ -decaying states, it is possible to investigate separately the lower- and higher-spin states in the daughter  $^{133}\text{Sn}$  and therefore to probe independently different single-particle transitions relevant in the  $^{132}\text{Sn}$  region. States having neutron-hole nature were identified in  $^{133}\text{Sn}$  at energies exceeding neutron-separation energy up to 3.7 MeV [3]. Due to centrifugal barrier hindering the neutron from leaving the nucleus ( $\ell = 4$  or  $5$ ), the contribution of electromagnetic decay of those unbound states was found to be significant. The same phenomenon was identified for a new neutron-unbound state observed in  $^{134}\text{Sn}$ . In addition to the previously known transitions following the  $\beta$  decay of  $^{134}\text{In}$  [4, 5], we firmly assigned 11  $\gamma$  transitions to the decay of  $^{134}\text{In}$  based on parent half-life and  $\gamma$ - $\gamma$  coincidences with the known  $\gamma$  rays depopulating states in  $^{134}\text{Sn}$ ,  $^{133}\text{Sn}$  and  $^{132}\text{Sn}$ .  $\beta$  and  $\beta 2n$  decay branches of  $^{134}\text{In}$  have been observed for the first time. Preliminary results of the first  $\beta$ -decay studies of  $^{135}\text{In}$  will be presented. A comprehensive description of excited states in  $^{134}\text{Sn}$ ,  $^{133}\text{Sn}$  and  $^{132}\text{Sn}$  was obtained from both  $\beta$  and  $\beta n$  decay branches of indium isotopes.

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## Low-energy physics / 27

# Shape coexistence in neutron-deficient mercury isotopes studied through $\beta$ decay

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The neutron-deficient mercury isotopes ( $Z = 80$ ) around  $N = 104$  represent one of the most prominent examples of shape coexistence [1]. This region has been extensively studied using various experimental techniques, such as laser spectroscopy [2,3], decay spectroscopy studies [4,5] and Coulomb excitations [6,7]. These studies point to the coexistence of two classes of states with strong mixing between the low-lying members in  $^{182,184}\text{Hg}$  [1,5-7]. In particular, the presence of  $E0$  components in the  $I \rightarrow I$  ( $I \neq 0$ ) transitions has been interpreted as a fingerprint for mixing [1].

In order to study the properties of the low-lying states in mercury isotopes around  $N=104$ , the  $\beta$  decay of  $^{182,184,186}\text{Tl}$  to excited states in  $^{182,184,186}\text{Hg}$  has been measured at the ISOLDE Decay Station (IDS). The conversion electrons have been measured for the first time at IDS by employing the newly developed SPEDE spectrometer [8], which provided an energy resolution of 7 keV for an electron energy around 250 keV. Compared to the previous study [5], an order of magnitude higher statistics was collected, which resulted in a significant decrease of statistical uncertainties in branching ratios and conversion coefficients.

In  $^{182}\text{Hg}$  the existence of the low-energy 16-keV  $2_1^+ \rightarrow 0_2^+$  transition was proven and its strength was determined to be in agreement with the Coulomb excitation study [7]. In addition, other experimental observables such as branching ratios and conversion coefficients, are in a good agreement with the previous measurements [5,7]. The results are compared to the two-state mixing model and a reasonable agreement is obtained.

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**Solid State Physics / 9**

## Diamond-based color center for quantum optics and quantum sensing applications

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Color centers in diamond are systems with appealing photo-physical properties for the development of quantum technologies. The ever-growing interest in these systems is motivated by their operation at room temperature, together with an ease of access and manipulation in a solid state system characterized by high transparency and structural stability, with applications as bright and stable single-photon sources or individual spin systems with optical readout, with record performances even at room temperature. Despite literally hundreds of optically active color centers in diamond have been reported in the past decades, only a handful of them can be consistently fabricated by means of a reproducible process such as ion implantation. Therefore, concurrently with the remarkable results achieved at the state of the art on the exploitation of the unique properties of the negatively-charged nitrogen-vacancy center (NV<sup>-</sup>), the quest for single-photon emitters with desirable properties still leads to the continuous discovery and characterization of new classes of optically-active defects.

In the present contribution, I will report on the joint research activities carried at the Italian National Institute for Nuclear Physics (INFN), the University of Torino and the Italian National Institute of Metrologic Research (INRiM) on the engineering by means of ion implantation of novel classes of quantum emitters in single crystal diamond for applications as single-photon sources. The exploitation of ion beam lithography techniques as a tool for the fabrication of integrated opto-electronic devices with tunable emission properties will also be discussed. Finally, I will introduce our recent results on the utilization of the unique spin properties of the NV<sup>-</sup>-center as quantum sensors for the high-resolution mapping of local magnetic and electrical fields in diamond-based devices.

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## Unambiguous identification of the split-vacancy configuration of the SnV<sup>-</sup> defect in diamond

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Point defects in diamond are being intensively investigated for their applications in processing and communication of quantum information, as well as for metrology. So far, the negatively charged nitrogen-vacancy center (NV<sup>-</sup>) has been the most studied defect [1]. Thanks to its efficient optical spin polarization and spin-state dependent fluorescence, it is being exploited, for example, in the

context of high-sensitivity magnetometers [2]. More recently, owing to their superior optical properties, the group-IV-vacancy centers (SiV- [3], GeV- [4], SnV- [5,6], and PbV- [7]) have emerged as one of the leading types of point defects for quantum computing and communication applications. Whereas it is generally accepted that the N atom in the NV- center occupies a substitutional C site, the group-IV atoms in group-IV-vacancy centers are expected to form a so-called split-vacancy configuration where they are centered in between two vacancies. However, experimentally, these structural configurations have so far been only indirectly determined. A detailed, direct and quantitative characterization of the structure of these defects is especially important for the field, since the superior properties of the group-IV-vacancy centers are to a large extent a consequence of the D3d inversion symmetry of the split-vacancy configuration rather than C3v, as in the case of NV-. The D3d symmetry, however, will only be found if the impurity is exactly centered in the double vacancy, which corresponds to the ideal bond-center (BC) position.

We have used the beta- emission channeling method from  $^{121}\text{Sn}$  ( $t_{1/2}=27.1$  h) implanted at the low fluence of  $2.3 \times 10^{12}$  atoms/cm<sup>2</sup> into natural diamond in order to identify the lattice sites of Sn and hence also possible configurations of SnV defects. Following room temperature implantation ~60% of the implanted  $^{121}\text{Sn}$  occupied substitutional sites, while ~40% was found on a position that corresponds to a bond-center site and which is attributed to the SnV split-vacancy configuration. While the as-implanted lattice location indicated displacements from the ideal S and BC sites of the order of ~0.15 Å, following annealing at 920°C ~70% of the Sn atoms were found on the ideal substitutional and ~30% on ideal bond-center positions. The same diamond sample was subsequently implanted with the stable isotope  $^{120}\text{Sn}$  and studied by means of confocal photoluminescence (PL) spectroscopy, which, after 920°C annealing, revealed the characteristic luminescence signal [5,6] of SnV- at a wavelength of 621 nm.

Besides  $^{121}\text{Sn}$ , suitable EC probes for further studies of group IV-vacancy centers could be  $^{31}\text{Si}$  (157 min),  $^{75}\text{Ge}$  (82.8 min), or  $^{209}\text{Pb}$  (3.2 h), and ideas for possible future experiments will be outlined.

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## Solid State Physics / 38

### Hyperfine studies on the structural phase transitions of the naturally layered perovskite $\text{Ca}_2\text{MnO}_4$

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Naturally layered perovskites (NLP) such as the Ruddlesden-Popper (R.P.) phases ( $\text{Ca}_{n+1}\text{Mn}_n\text{O}_{3n+1}$ ) have appeared as a fascinating route to achieve nonexpensive room temperature multiferroic mate-

rials. In these NLP, specifically in the  $\text{Ca}_3\text{Mn}_2\text{O}_7$  compound, distortions of the lattice such  $\text{MnO}_6$  octahedron rotation and tilting modes couple to polar cation dislocation modes inducing a ferroelectric polarization, in a mechanism known as hybrid improper ferroelectricity. The revived interest in this compound lead us to study the homologous elements belonging to the R.P. series. In particular,  $\text{Ca}_2\text{MnO}_4$  although non polar presents similar  $\text{MnO}_6$  octahedral rotations and, just as  $\text{Ca}_3\text{Mn}_2\text{O}_7$ , exhibits also the unusual uniaxial negative thermal expansion.

Perturbed Angular Correlation  $\gamma$ - $\gamma$  (PAC) hyperfine technique offers a unique opportunity to probe at the local scale the structural, charge and magnetic phase transitions of these NLP systems. The measurement of the electric field gradient (EFG) allows to probe accurately the octahedral  $\text{MnO}_6$  rotations that underlie the material's structural transitions. At ISOLDE-CERN, by using metastable  $^{111\text{m}}\text{Cd}$  isotopes as radioactive probes, PAC measurements were performed in an extensive range of temperatures (1200K - 11K) on the  $\text{Ca}_{n+1}\text{Mn}_n\text{O}_{3n+1}$  series. In the  $\text{Ca}_2\text{MnO}_4$  compound we have measured for the first time the structural transition that occurs at high temperature from  $I4/mmm$  to the lower temperature  $I4_1/cad$  structure. Moreover in the temperature range of 1000K to 10K we only saw evidence for a single local environment, disagreeing with the previously results obtained by transmission electron microscopy measurements at room temperature conditions, that proposed a coexistence of two distinct structural phases  $I4_1/cad$  and  $Aba2$ . Combined ab-initio electronic structure calculations were also performed to understand and show how the measured EFG at the probing sites is sensible to the distinct  $\text{MnO}_6$  octahedron distortion modes.

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### Lattice location of $^{229}\text{Th}$ in $\text{CaF}_2$

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The  $^{229}\text{Th}$  nucleus can be excited to a nuclear isomer state with an extremely low excitation energy of  $8.28 \pm 0.17$  eV. This excited state is within range of current laser technologies, making it an ideal candidate for optical nuclear clock applications. However, the production of such a nuclear clock is hindered by that same low excitation energy, which is of the order of typical electronic shell transitions and larger than the first ionization potential, allowing for internal conversion (IC) to be the dominant decay channel. The implementation of an IC blocking mechanism would therefore enable further studies of the isomer radiative decay and of its exploitation in the context of optical nuclear clock applications. Based on density functional theory calculations, it has been proposed that IC blocking can be achieved by incorporating the  $^{229}\text{Th}$  atoms into a  $\text{CaF}_2$  crystal, occupying substitutional Ca sites [1]. Since this configuration preserves the large bandgap of  $\text{CaF}_2$  (12 eV), without formation of gap states, electronic transitions at the isomer energy are forbidden, thus blocking IC.

In order to determine the lattice location of  $^{229}\text{Th}$ ,  $^{229}\text{Ac}^+$  ions were implanted (at 30 keV) into a  $\text{CaF}_2$  single crystal at the EC-SLI set-up. The  $\beta^-$  emission channelling patterns from  $^{229}\text{Ac}$  were measured in the vicinity of the  $\text{CaF}_2$   $\langle 211 \rangle$ ,  $\langle 111 \rangle$ ,  $\langle 100 \rangle$  and  $\langle 110 \rangle$  directions. Because the  $^{229}\text{Th}$  daughter nuclei are recoiled with an energy of only 2.3 eV, below typical threshold displacement energies, they are expected to occupy the same lattice sites as those determined for  $^{229}\text{Ac}$ . Preliminary analysis shows that the majority (at least 75 %) of the  $^{229}\text{Ac}$  atoms occupy Ca substitutional sites. In addition, thermal annealing and high temperature implantation are observed to affect the  $^{229}\text{Ac}$  root-mean-square displacement from the ideal Ca substitutional site, which suggests that additional lattice defects (e.g. neighboring F vacancies) may be involved. We will discuss to what extent

these high-temperature processes can be exploited to optimize the Ca substitution, towards future studies of the isomer radiative decay and of its exploitation in the context of optical nuclear clock applications.

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## HIE-ISOLDE physics / 10

### Halo effects in the low-energy scattering of $^{15}\text{C}$ with heavy targets

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Nuclear systems such as  $^6\text{He}$ ,  $^{11}\text{Li}$  or  $^{11}\text{Be}$  are known to have an extended neutron distribution, the so-called neutron halo. The halo can be formed in nuclei close to the neutron drip line, where the separation energy of valence neutrons is small and the nuclear barrier becomes thin enough for the neutrons to tunnel out with larger probability. This effect enhances the diffuseness of the nuclear surface, leading to an extended density distribution. The halo structure has been observed in high-energy scattering measurements ( $\sim 100$  MeV/u) from the narrow momentum distribution of breakup fragments and the large value of the interaction cross sections. At low collision energies ( $\sim 5$  MeV/u), the effect of the halo structure was for first time demonstrated by the strong absorption pattern found in the elastic cross sections, where the nuclear rainbow completely disappears. In the case of  $^6\text{He}$  and  $^{11}\text{Li}$  scattering this suppression can be attributed to the large neutron transfer and breakup probabilities.

In this work we present the first results on the low-energy scattering of the halo nucleus  $^{15}\text{C}$  with a  $^{208}\text{Pb}$  target at collision energies just around the Coulomb barrier. The isotope  $^{15}\text{C}$  is weakly bound for one-neutron removal by only 1218 keV, being the only known case of a pure  $2s_{1/2}$  neutron-halo configuration. The experiment (IS619) was carried out at the XT03 beamline of the HIE-ISOLDE facility at CERN (Switzerland), using the GLORIA detector array and the SEC scattering chamber. Two high-purity  $^{208}\text{Pb}$  targets (>98%) of 1.5 mg/cm<sup>2</sup> and 2.1 mg/cm<sup>2</sup> were used for the measurements. The  $^{15}\text{C}$  beam was produced using a  $\text{CaO}_2$  primary target on a hot-cathode plasma source. Details of experiment and preliminary results on the angular distribution of the elastic cross sections will be presented and discussed in the framework of optical model calculations.

## HIE-ISOLDE physics / 4

### Elastic scattering of p-halo $^8\text{B}$ beam close to the Coulomb barrier

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In this contribution, preliminary results of the experiment IS616 will be presented. The aim of the experiment was to investigate on the reaction dynamics of proton-halo induced collisions at energies around the Coulomb barrier where coupling to continuum effects are expected to be important. The elastic scattering  $^8\text{B}+^{64}\text{Zn}$  angular distribution was measured, for the first time, using the GLORIA Si-strip detector array placed in the SEC scattering chamber. The low beam intensity hindered the possibility to measure  $p\text{-}^7\text{Be}$  coincidences coming from break-up processes. Singles events have, however, been measured.

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## Progress of the IS559 experiment

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The IS559 experiment is the first ever attempt of utilising the Oslo Method with a radioactive beam in inverse kinematics reactions. A  $^{66}\text{Ni}$  beam with 4.5 MeV/u hit a deuterated polyethylene target for a total of  $\approx 10$  days. The ultimate goal of the experiment is to look for particle-gamma coincidences from the  $d(^{66}\text{Ni},p)^{67}\text{Ni}$  reaction, reconstructing the excitation energy from the proton energy on an event-by-event basis. Six large volume ( $3.5\times 8''$ ) LaBr3:Ce detectors were coupled to the Miniball setup to boost the overall gamma detection efficiency while the charged particles were detected with the C-REX silicon setup. From the resulting excitation energy -  $\gamma$ -ray energy spectra we have extracted the level density and  $\gamma$ -ray strength function.

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## The ISOLDE Solenoidal Spectrometer - recent highlights and future developments

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The first two physics experiments using the ISOLDE Solenoidal Spectrometer (ISS) have both been a success. This talk will present the final results from the two measurements made before LS2. The  $^{28}\text{Mg}(d,p)^{29}\text{Mg}$  reaction, carried out at 9.5 MeV/u, probed single-particle structure near the island of inversion. This measurement revealed the structure of the low-lying negative-parity intruder states, enhancing our understanding of how they evolve in this region of the nuclear chart. At the other end of the nuclear chart, the second measurement with ISS was the  $^{206}\text{Hg}(d,p)^{207}\text{Hg}$  reaction, carried out at 7.4 MeV/u. Single-particle excitations in this unexplored region of the nuclear chart were identified for the first time. The spectroscopy of  $^{207}\text{Hg}$  is the first step in extending our knowledge of nuclear structure towards r-process nuclei in this region. These measurements demonstrate the versatility of ISS as a charged-particle spectrometer capable of exploiting beams of all masses from ISOLDE.

Progress and plans for the new detector systems for ISS, which are due to be commissioned during LS2, will also be presented. These include the new silicon array that has been constructed by the University of Liverpool, a fast-counting recoil detector for identifying reaction products and an array of fission-fragment detectors for probing transfer-induced fission - both under construction at The University of Manchester.

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## Two-Neutron transfer into the "Island of Inversion" at HIE-ISOLDE

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In the so-called "Island of Inversion" around 32Mg, the ground states of nuclei exhibit larger binding energy than expected from simple models. Extra binding energy can stem from the onset of deformation. Indeed, the systematics of excitation energies and B(E2) values in the Mg isotopes indicate a softening of the N=20 shell closure and it was suggested that the nuclear tensor force has a major influence. Recently, a shell model interaction for the entire sdfp shell model space was deduced using the EKK-theory from realistic nucleon-nucleon interactions without a fit of two-body matrix elements. The new prediction is a drastic change to the earlier belief: the calculations suggest that only 25% of the groundstate in 30Mg is made from 0p0h contributions, whereas 50% and 25% are due to 2p2h and 4p4h configurations, respectively. This contrasts with all previous investigations, like the E0 measurement in 30Mg, performed at ISOLDE, which all conclude that 2p2h and 4p4h contributions in the groundstate of 30Mg are as small as 5%.

We present new data from experiment IS651 at the new HIE-ISOLDE facility, CERN. An intense radioactive beam of 28Mg ( $1.5 \cdot 10^6$ pps) was scattered off a radioactive tritium target to populate states in 30Mg after two-neutron transfer. For the first time, the full HIE-ISOLDE beam energy of 9.5 MeV/u was used for a transfer experiment at MINIBALL. Thanks to the higher beam energies, the data allow insight into the full complexity of three-state mixing in the IOI, for the first time. We discuss the implications of the preliminary data analysis to our understanding of nuclear shell evolution.

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## Transfer and breakup reactions involving <sup>7</sup>Be at ISOLDE

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The transfer and breakup nuclear reactions involving loosely bound light stable and unstable nuclei have interesting consequences in nuclear astrophysics. In particular, reactions with  ${}^7\text{Be}$  are linked to the cosmological lithium problem. Detailed studies of  ${}^7\text{Be}$  destruction channels are required before one can invoke solutions to the lithium problem beyond nuclear physics, particularly in the context of new resonances as well as conjectured light neutral particles. In addition, study of  $\alpha$ -transfer and breakup reactions involving  ${}^7\text{Be}$  require data on different targets with wide angular coverage. An experiment with 5 MeV/A  ${}^7\text{Be}$  on  $\text{CH}_2$ ,  $\text{CD}_2$  and  ${}^{208}\text{Pb}$  targets has been carried out at HIE-ISOLDE (IS 554). We utilized the scattering chamber installed in the third beamline of the HIE-ISOLDE facility with sets of DSSD in a pentagon geometry. Preliminary results from the experiment would be presented.

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## Young Speaker and Poster Prize Announcements

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### Search for beta-delayed proton emission from ${}^{11}\text{Be}$

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This contribution reports the final results of the IS541 experiment that searched for beta-delayed proton emission from  ${}^{11}\text{Be}$  through detection of the final state nucleus  ${}^{10}\text{Be}$  with accelerator mass spectrometry, coupled to a determination of the  ${}^{11}\text{Be}$  intensity via gamma decays. A first experiment (published 2014 [1]) reported an observation of the decay branch. In a follow-up experiment twelve samples were collected at ISOLDE at different separator settings, allowing tests of different sources of contamination to be made. The observed amounts of  ${}^{10}\text{Be}$  per collected  ${}^{11}\text{Be}$  rule out several contamination sources, but do not agree internally and seem to be inconsistent with a recent experiment from TRIUMF [2]. Possible explanations for the disagreement will be discussed.

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### Disentangling the ${}^{186}\text{Hg}$ puzzle

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Neutron-deficient Hg nuclei have been the subject of intensive experimental and theoretical research since the 1970s. Actually, the first direct evidence for shape coexistence near the  $Z=82$  shell closure was obtained for neutron-deficient mercury isotopes by means of isotope shift measurements [1]. These measurements showed that there is a unique staggering in the variations of the mean-square charge radii pointing to shape effects and shape coexistence. Very recently these measurements were revisited at ISOLDE marking the limits of this unique behaviour [2]. In this context studying the shape of the  $182,184,186\text{Hg}$  even-even systems is of particular interest, since they lie next to the systems where the staggering takes place.

The beta decay of  $186\text{Hg}$  has been studied at ISOLDE using the total absorption spectrometer LUCRECIA in order to infer the ground state shape of this nucleus from the distribution of the beta strength in the daughter [3], in a similar fashion to the works [4-8]. This kind of study is feasible whenever there are different patterns in the beta strength depending on the shape of the parent nucleus (see for example the theoretical works [9-12]). In this contribution we will present the challenging analysis of this experiment and its possible interpretation.

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