ISOLDE Workshop and Users meeting 2014 ”50th Anniversary Edition”

Monday, 15 December 2014 - Wednesday, 17 December 2014

CERN

Book of Abstracts

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Mass spectrometry and decay spectroscopy at CARIBU

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A new facility for the production of short-lived neutron-rich isotopes, CARIBU, is now operational at Argonne National Laboratory. CARIBU, the Californium Rare Ion Breeder Upgrade (CARIBU) of the ATLAS superconducting linac facility, provides low energy and reaccelerated neutron-rich radioactive beams to address key nuclear physics and astrophysics questions. These beams are obtained from fission fragments of a 252Cf source, thermalized and collected into a low-energy particle beam by a large helium gas catcher, mass analyzed by an isobar separator, and charge bred to higher charge states for acceleration in ATLAS. The approach employed at CARIBU is fast and universal and short-lived isotopes are extracted with a yield essentially following the Californium fission distribution. Over 110 neutron-rich species have been extracted and used for experiments so far. The facility will be described and results from measurements at low energy and with reaccelerated beams will be given.

This work was supported by the US DOE, Office of Nuclear Physics, under contract DE-AC02-06CH11357.

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Laser and mass spectroscopy at SLOWRI of RIKEN RIBF

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A universal stopped and low-energy RI-beam facility (SLOWRI) [1] is finally being installed at RIKEN RIBF. It will convert relativistic RI-beams from the inflight separator BigRIPS to low-energy, low-emittance, high-purity RI beams using two different gas catcher cells: RF-carpet gas cell and PALIS gas cell [2, 3]. The former is a 1.5-m long cell filled with 100 mbar He gas and operated at 77 K cryogenic temperature. It will be placed at the exit of D4 magnet of BigRIPS to accept main beams from BigRIPS. The thermal ions in the large cell can be transported quickly toward the exit by a large RF-carpet [4, 5] with the ion-surfing method [6, 7, 8]. The latter cell will be placed in the vicinity of F2 focal plane of BigRIPS where unused RI-beams were simply abandoned. The cell is 30 cm long and filled with 1 bar Ar gas in which most thermal ions quickly become neutral. The neutral RI atoms can be transported by a gas flow toward the exit where resonant laser radiations re-ionize the atoms selectively. This gas cell will be used concurrently with the other BigRIPS experiments so that parasitic low-energy experiments can be carried out everyday.
The extracted RI-beams from the gas cells will be mass separated by dipole magnets at 30 keV and the beams will be merged into a single beam line leading to the experimental room where various precision spectrometers such as a multi-reflection time-of-flight mass spectrograph [9, 10, 11], ion traps [12, 13] and a collinear laser spectroscopy apparatus will be placed and users

can access the room without any restrictions. Many experiments and tuning the spectrometers can be conducted daily using the parasitic beam; the main beam will be required only when very rare isotopes are studied.
At SLOWRI, various precision spectroscopy experiments will be performed. One is laser spectroscopy for the electromagnetic ground state properties of exotic nuclei, especially for so called 'difficult'elements which are not available at originally ISOL facilities. The other is precision mass measurements with the MRTOF mass spectrograph. It will be able to determine multiple nuclei simultaneously when directly coupled with gas catcher at BigRIPS.

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Facility for Rare Isotope Beams under Construction

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FRIB, the US's "Facility for Rare Isotope Beams"at Michigan State University (MSU), will be based on a 400 kW, 200 MeV/u heavy ion linear accelerator. Once realized, FRIB will be a world-leading rare isotope beam facility, providing a wide variety of high-quality beams of unstable isotopes at unprecedented intensities, opening exciting research perspectives with fast, stopped, and reaccelerated beams. NSCL, the present premier rare isotope beam user facility in the US, enables pre-FRIB science and will eventually be integrated into FRIB. This talk will review present the FRIB facility and its science opportunities, and summarize the status of the project for which construction has started.

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Status and highlights from ISAC/TRIUMF

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The ISAC facility at TRIUMF with its ISOL-based radioactive beam operation with up to 50kW production targets offers some unique research capabilities to its 18 permanently installed (and 3 general purpose experimental stations) experiments. ISAC has been operational for over 15 years and its experimental program includes nuclear structure studies, electroweak-precision studies, nuclear astrophysics, and material science. It has a low-energy (60keV) medium-energy (up to 1.8 MeV/u) and high energy (up to 16 MeV/u) experimental area. In addition, TRIUMF is building a new electron-accelerator-based photo—fission ISOL facility, called ARIEL (Advanced Rare IsotopE Laboratory) which will provide two radioactive beams to the experimental areas. A first milestone for ARIEL has recently been reached with the acceleration of electrons to over 20 MeV. In this presentation I

will give an overview and show highlights of the ISAC experimental program as well as the ARIEL project.

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Medical Isotope Production and Use, with a special view on the need for ISOLDE and other big science facilities

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Medical use of radioactive isotopes for diagnosis and therapy is a widespread and commonly accepted application of radioactivity. It has historical roots back to Curie, Hevesy and Lawrence, and while the principles are the same as a 100 years ago, the number of applications, their sophistication and precision, and not least the clinical benefits are growing each day.

Although "new"isotopes are being introduced to medicine each year, by far the most procedures are carried out using just a dozen of well known and trivial radioisotopes, either derived from fission of uranium in reactors or from simple compound nuclear reactions in small to medium energy accelerators. As the talk will explain some of the large scale infrastructure necessary for continuous growth of nuclear medicine is now under attack, as is the case with the aging research reactors used for Mo-99 and I-131 production. New facilities and new technologies can fill in the gap, if conceived, funded and build in time, but decisions and foresight is needed now.

Big Science facilities do not easily fit into such demanding routine production commitments, but they may very well help demonstrate and develop the technology needed. Production of neutrons by spallation and extraction of isotopes from spallation targets are good examples. There are also cases of some isotopes with special imaging or therapy applications, where spallation and isotope separation is the only road to get them, and these examples will be discussed.

However, big science involvement is not the ultimate answer to the needs of nuclear medicine. A recent and very interesting development is the global dissemination of hundreds of small medical cyclotrons, initially intended only for PET, but each also capable of making other isotopes than F-18 and C-11. Even therapeutic applications are conceivable with this "cottage industry"platform. It has the benefit of flexibility, multiplicity, quick reaction time and very simple distribution logistics,- and in this way much more failure-resistant. Perhaps it can even be characterised as "sustainable". With further development of chemistry and automation, it may well change and improve the future use of nuclear medicine imaging.

The talk will try to use past and present experience to predict the future role and the future gaps in medical use of radioactive isotopes.

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Development of a networked and modular personal dosimetry system

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We will describe the development of a personal radiation level monitoring system based on an autonomous, advanced dosimeter, which takes advantage of a scintillator-SiPM combination and integrates isotope identification capabilities.

The measurements are time and position stamped, including indoor locations. The device implements Wireless Sensor Networks access in such a way that several networked personal dosimeters can be addressed as mobile sensors providing a high sampling rate over an extended area.

The dosimetry system is modular, including three main elements: the Personal Dosimeters themselves, a Wireless Gateway deployment and a Central System, which is a web-based remote storage, monitoring and management system.

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Beta-delayed particle emission from ^{21}Mg

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The beta-decay of the proton rich nuclei ^{21}Mg was used as a calibration source for the IS507 experiment. The aim of the experiment was to study the beta-decay of ^{20}Mg with a dedicated charged particle detection setup consisting of two opposing ΔE-E telescopes. As ^{21}Mg is close in mass to ^{20}Mg and is a known beta-delayed proton emitter, with intense proton branches, it is suitable for energy calibrations. A closer look at the data reveals new decay channels not previously seen in the decay of ^{21}Mg. Clear signs of beta-delayed alpha emission and new beta-delayed proton channels were evident.

A detailed investigation of the alpha spectrum has led to the conclusion that four beta-delayed alpha branches are measured, ^{21}Mg(β)^{21}Na(α)^{17}F, going through high-lying resonances in ^{21}Na. Coincidences between the two opposing ΔE-E telescopes have led to the conclusion that a weak decay channel via the decay chain ^{21}Mg(β)^{21}Na(p)^{20}Ne(α)^{16}O is also seen for the first time.

The proton spectrum measured gives rise to a new interpretation of the decay scheme. Due to the use of a DSSSD detector beta summing is reduced to a negligible level. Together with recent measurements of elastic scattering of protons on ^{20}Ne this has led to a new tentative interpretation of the decay scheme. Confirmation of this new interpretation would be possible in the remaining beam time at the new ISOLDE Decay Station, where detection of coincident gamma rays is possible.

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In Gas Laser Ionization and Spectroscopy of neutron deficient 212-215Ac isotopes

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The In-Gas Laser Ionization and Spectroscopy (IGLIS) technique was employed at the LISOL facility to produce radioactive beams of high purity and obtain important information on the nuclear ground- and excited-state properties of, e.g., neutron deficient copper [1] and silver [2]isotopes. Recent experiments on the actinide region have allowed us to efficiently produce beams of neutron deficient actinium isotopes from ^{212}Ac to ^{215}Ac, in the N=126 shell closure, and perform detailed in-gas-cell laser spectroscopy of the $^2D_{3/2} \rightarrow ^4P_{5/2}$transition at 438 nm with a relative spectral resolution $\delta\nu/\nu$=1·10^{-5}.
Unlike in-gas cell laser spectroscopy studies, laser ionization in the low-temperature and low-density gas jet allows eliminating the pressure broadening thus improving the spectral resolution by, at least, one order of magnitude ($\delta\nu/\nu$=5·10^{-7}), as recently demonstrated in off-line experiments on the stable copper isotopes [3].

In the HELIOS laboratory, being commissioned at KU Leuven, the formation of supersonic gas jets using a de Laval nozzle will be investigated in off-line experiments in parallel to tests of a new gas cell design and the characterization of a new high-power high-repetition pulse rate laser system. Visualization of the jets by planar laser induced fluorescence will be carried out to determine the best experimental conditions to perform laser spectroscopy with an enhanced resolution in the new radioactive beam facility S^3 at SPIRAL2 [4].

Results on the isotope shifts and the magnetic moments of the actinium isotopes will be reported in this talk and a summary on the experimental activities to optimize the IGLIS technique at the offline HELIOS laboratory will be presented.

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Developments for the ISOLDE resonance ionization laser ion source RILIS

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The long shutdown (LS1) provided an opportunity for ionization scheme and ion source development for the ISOLDE resonance ionization laser ion source (RILIS), in addition to several upgrades to the general RILIS set up. Several of these results will be presented along with a summary of the current RILIS status.

New RILIS ionization schemes have been successfully developed and tested for Ba, Li, Ge, Hg, and Cr. What is believed to be the world's first resonance ion-ionization in a hot cavity was demonstrated, creating Ba2+ to meet a specific need to eliminate the problem of a surface ionized isobaric background from beams of 112-118Ba. The first demonstration of resonance laser ionization inside the VADIS, ISOLDE's FEBIAD type ion source, was demonstrated off-line with gallium. This RILIS Mode operation of the VADIS cavity was then successfully applied on-line, coupling a molten Pb target with RILIS for the first time, to produce laser-ionized beams of neutron-deficient mercury isotopes[1].

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The ISOLDE robot upgrade

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During the LS1 a major safety upgrade was held at ISOLDE, the complete robotic system for the target exchange has been replaced. This upgrade was done in order to improve the operation and the safety of the facility. This presentation will explain the different phases of the project from the idea of upgrading the system to it final operation and although the future evolution of the system.

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The TWINEBIS test bench

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For more than a decennium REX-ISOLDE has been a key element at the ISOLDE radioactive beam facility. The post-accelerator consists of a Penning trap for bunching and cooling of the 1+ ions delivered from ISOLDE, an EBIS for charge breeding and a LINAC for the actual acceleration. It has delivered over 100 different radioactive radionuclides with an energy of a few MeV/u. While successful, the high beam demand has not allowed for intrusive machine studies to be carried out at the REX facility. In the case of the EBIS, several issues could not be investigated with the required thoroughness, for instance cathode poisoning and electron current limitations. Neither could time-modulation of the extracted ion pulse in order to match the very short injection time of the suggested TSR@ISOLDE setup, or long uniform extraction time for fixed target experiments that are presently affected by dead-time effects in detectors and/or data-acquisition systems be explored properly. Furthermore we would like to test a different type of cathode material, IrCe, which is used at other laboratories. Here the interest lies in the extractable electron current and the cathode lifetime as compared to the routinely used LaB6.

Therefore, during the last few years a dedicated offline EBIS test bench, TwinEBIS, has been setup at CERN. The EBIS is a copy of the REXEBIS, although with minor modifications in the drift-tube structure, a more versatile control system and with no injection presently available. The TWINEBIS setup has been commissioned and several investigations have begun. In this contribution an overview of the setup and the first results will be given.

By end of October we will embark on TWINEBIS - phase 2. It includes the move of the system to a more spacious laboratory area, which allows adding an injection ion-source and an analysis magnet to investigate charge breeding times for different elements as function of different settings of the

EBIS, for example electron current and density, magnetic field etc. The layout of the new test facility will also be presented.

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Development progress of a charge breeder for HIE-ISOLDE and TSR@ISOLDE

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As part of the HIE-ISOLDE design study options for a new high-performance successor to the REXEBIS charge breeder have been investigated. In a parametric study based on the HIE-ISOLDE linac upgrade, and a possible future extension of HIE-ISOLDE by TSR@ISOLDE, a set of design requirements for the new breeder was elaborated.
In collaboration with the Advanced Ion Sources group at Brookhaven National Lab a research program was initiated. Based on a BNL design a high-compression electron gun was built at CERN and shipped to BNL, commissioned, tested and brought to operation on the full scale TestEBIS. The electron beam was extracted from the gun, guided to the full compression region, transported through the ionization region, which has a comparable length to a HIE-ISOLDE breeder, and efficiently absorbed in the collector. The beam was transmitted in a magnetic field strength up to 3.3 T over about 4 meters distance. In these experiments we achieved electron currents up to 1.7 A and the electron energy was approximately 35 keV. This is a significant step towards the full HIE-ISOLDE charge breeder specifications of 3.5 A and 60 keV (up to 150 keV for TSR@ISOLDE). We have identified potential sources of a 20 mA loss current limiting the transmitted current to 1.7 A. At the moment, a series of design modifications is on the way to address and mitigate the limiting loss. In a series of preliminary experiments the electron beam was used to ionize residual gas in the unbaked EBIS vacuum chamber.
During the autumn of 2014 the experimental research is continued. At BNL an upgraded electron gun with enhanced optics is under preparation. At CERN we are building diagnostics tools to analyze the charge-state distribution, energy distribution and emittance of the charge bred ions during the commissioning. Furthermore we continue the design studies by addressing the required modifications in order to allow changing the electron collector optics from immersed flow electron-beams with 20-25% duty cycle to high compression beams of near 100% duty cycle.
In this presentation we would like to give a summary of the R&D on the upgrade of the HIE-ISOLDE charge breeder. We will present a revised parametric study, recent experimental results, experimental plans for the nearest future and the longer development perspective.

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LIEBE: Design of a molten metal target based on a Pb-Bi loop at CERN-ISOLDE

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Future perspective for physics measurements at CERN-ISOLDE call for the use of molten metal targets to improve the yield of radioactive isotopes delivered to the experiments and better handle the high power density from the beam. CERN launched in 2012 an R&D project called LIEBE to investigate the feasibility of testing on line a Pb/Bi loop target compatible with the present installations at ISOLDE. While ISOLDE will be able to deliver a maximum of 10 kW of beam power, the power density on target is comparable to those available in existing or future facilities as EURISOL.

The design of the loop has been performed in collaboration with SCK-CEN, CEA, PSI, IPOOL and the prototyping phase has now started. The design of this target includes key components that never been integrated in an Isolde target before such as a heat exchanger to evacuate the high power deposited by the beam and an electromagnetic pump to ensure the circulation of the liquid metal. In the same time, the designs proposed for the irradiation and diffusion chambers have been optimized to allow a faster release of the produced isotopes. All these elements need to be extensively tested before the on-line installation of the target and the prototyping phase has now started.

This talk focuses on the development of the element of the liquid metal loop target, presenting the challenges due to the different constraints involved and developing the proposed target design. Finally, an overview of the results of preliminary tests will be presented while future prototypes and tests will be introduced.

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CATHI and the HIE-ISOLDE Design Study

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Financed by the European Commission within the Marie Curie Actions-ITN program, the CATHI (Cryogenics, Accelerators and Targets for Hie-ISOLDE) was launched in 2010 with the recruitment of 20 researchers; 11 of whom completed their training while working on different aspects of the HIE-ISOLDE Design Study. As the project terminates in 2014, their work will be collected in a final report that will provide a baseline for the upgrade of both the ISOLDE facility in order to accommodate a potential increase in proton-beam power and an improvement of beam quality through a new layout of the High Resolution Mass Spectrometer.
This presentation will highlight the achievements of the CATHI Fellows and will attempt to project future changes of the facility necessary to implement improvements identified in the HIE-Design Study.

Ground-State Properties / **3**

Nuclear Structure Theory: today and tomorrow

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The long-term vision of nuclear theory is to arrive at a comprehensive and unified description of nuclei and their reactions, grounded in the interactions between the constituent nucleons. Theorists seek to replace current phenomenological models of nuclear structure and reactions with a

well-founded microscopic theory that delivers maximum predictive power with well-quantified uncertainties. A new and exciting focus in this endeavor lies in the description of exotic and short-lived nuclei at the limits of proton-to-neutron asymmetry, mass, and charge.

In this talk, theoretical advances in rare isotope research will be reviewed in the context of the main scientific questions. Particular attention will bo given to the progress in theoretical studies of nuclei due to the advent of extreme-scale computing platforms.

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Structure of Potassium and Calcium isotopes studied by Collinear Laser Spectroscopy

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We have investigated the ground state structure of K and Ca over a wide range of isotopes, from below N=20 across the N=28 shell gap using the bunched-beam collinear laser spectroscopy technique. Thanks to the background reduction using the bunched-beam correlation method and the improved optical detection using a newly-designed detection set-up, experiments could be extended for both K and Ca up to N=32 (51K and 52Ca respectively).

From the magnetic moments and spins of the K isotopes, the evolution of the proton single particle levels can be studies as the neutron p3/2 level is being filled [1,2]. The isotope shifts provide information on the change in mean square charge radii across the N=28 shell gap, showing a strong increase towards N=32, both for K and Ca [3,4]. The isomer shift in the N=Z mirror nucleus 38K reveals the importance of proton-neutron pairing correlations in the 0+ isomeric state [5]. The magnetic and quadrupole moments of the 47,49,51Ca ground states provide a stringent test to recent calculations including 3N interactions [6].

Highlights from these experiments will be presented.

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The CRYRING@ESR project - status and prospects

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The CRYRING@ESR project is the early installation of the low-energy storage ring LSR, the Swedish in kind contribution to FAIR, which was proposed as the central decelerator ring for antiprotons at the FLAIR facility. Since the modularized start version of FAIR does not include the erection of the FLAIR building, it was proposed to install the CRYRING storage ring behind the existing experimental storage ring ESR already now. This opens the opportunity to endeavor part of the low energy atomic physics with heavy, highly charged ions as proposed by the SPARC collaboration but also experiments of nuclear physics background in the NUSTAR collaboration much sooner than foreseen in the FAIR general schedule. Furthermore, since the installation of the ring will be handled mostly by FAIR standards, it will be used to test major parts of the FAIR control system for the first time and well ahead of time before it is needed to run SIS100.
Rare ions for storage in CRYRING@ESR are produced and separated in the FRS and then stored, cooled and decelerated in the ESR. This imposes a lower life time limit of several ten seconds for ions available for experiments in the storage ring at energies between several 100 keV/nucleon and about 10 MeV/nucleon. A future connection to the Super FRS at FAIR would increase the available yields of rare, heavy and highly charged ions considerably and hence also extend the physics oportunities.

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High-precision mass measurements of 129-131Cd and their impact on nuclear astrophysics

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The high-precision mass spectrometer ISOTLRAP has been pioneering Penning-trap mass measurements of exotic nuclei already since 1987, when it was installed at the ISOLDE 1 facility, connected to CERN's Synchrocyclotron (SC). After the move of ISOLDE to the Proton Synchrotron Booster (PSB) in 1990, the ISOLTRAP experiment reassumed its successful mass-measurement campaign on short-lived nuclei, which continues until today [1].

During the recent first long shutdown of CERN (LS1), ISOLTRAP has undergone a prolonged maintenance operation, including a full refurbishment of its superconducting magnets. With the restart of physics at ISOLDE in the summer of 2014, ISOLTRAP contributed to a number of experiments.

The contribution will briefly report on the work that was performed during LS1 and describe the current status of the setup. The results of the first successful beam times of 2014 will be discussed. One of the highlights is the mass measurement of the r-process waiting-point nuclide 130Cd and of its neighbors 129,131Cd. In addition, ISOLTRAP contributed to the study of the hyperfine structure of astatine isotopes by in-source laser spectroscopy and allowed yield studies of different ISOLDE beams in support of on-going target and ion source developments.

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Recent highlights and future possibilities in ferromagnetic semiconductors

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The epitaxial diluted magnetic semiconductor (Ga,Mn)As is a model system for investigating spin and spin-orbit phenomena in magnetic and semiconducting systems. Studies of this compound have led to the elucidation of new functionalities in experimental spintronic devices, including optical and electrical control of the magnetic order, with general applicability to a wide range of material systems. This talk will review the basic material properties of (Ga,Mn)As and recent progress in understanding its electronic, magnetic and structural properties, including the mechanisms limiting its Curie temperature. Future prospects for new materials, with functionality at elevated temperatures, will be discussed.

Solid State Physics / **20**

Carrier Mobility and Magnetic Interactions in TiO2

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Thin films and powder samples of intrinsic and transition metal doped titanium dioxide were investigated by an atomic resolution hyperfine nuclear technique in order to study the relation between defects and ferromagnetism. Complementarily, the crystalline structure, morphology and composition of the samples were investigated by X-ray diffraction (XRD), scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) characterization techniques. Magnetic properties were further investigated by magnetization measurements using a vibrating sample magnetometer (VSM). Hyperfine parameters were studied as a function of temperature by means of perturbed gamma-gamma angular correlation (PAC) spectroscopy using different probe nuclei 111In/111Cd, 181Hf/181Ta and 111mCd/111Cd. Thin films of 88-100 nm thickness were deposited by magnetic sputtering on Si (100) substrates, inducing the formation of the rutile phase. Doping of the films with Fe and Co was achieved by ion implantation and the powder samples were prepared by the Sol Gel Method. PAC measurements were carried out after implantation of 111In or 181Hf at the BONIS implanter in Bonn University, with and without magnetic field applied and after 111mCd at ISOLDE laboratory. After the initial measurements carried out as implanted, the samples were annealed at 600°C in vacuum or air, which allowed the permanence of defects caused by the implantation process and voluntarily lead to the formation of the Magnéli phases. PAC results show the presence of up to three site fractions for the probe nuclei depending on the heat treatment. One is assigned to the probe nuclei at the substitutional Ti sites and the other two can be assigned to defect sites, either near the doping ions or near shear planes, which gives rise to the observed magnetic interaction on the atomic scale PAC data and on a macroscopic scale magnetometry data. However, the most important result of this work was the correlation between the magnetic interactions and the observed rearrangement of the charges as a function of the temperature for all the three different probe elements nuclei. This means that the recombination of local charge carriers can be associated with the macroscopic observation of the hysteresis curves obtained by magnetometry, an effect that is enhanced with the decrease of the temperature.

Solid State Physics / 13

Fighting f-factors and implantation damage in emission Mössbauer spectroscopy

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The Mössbauer collaboration at ISOLDE/CERN applies short lived isotopes for emission Mössbauer spectroscopy (eMS) within material sciences. Mössbauer spectroscopy (MS) gives various detailed information on the probe atoms, through the hyperfine interactions. There are several benefits of eMS in particular we can perform measurements in the extremely dilute regime (~10^{-4} at. %) and make use of the chemical nature of the parent (implanted) atom.

In cases, where we want to study defect physics, the implantation damage is beneficial. In other cases it can impede investigations. Conventionally, we implant/measure at elevated temperatures to monitor the annealing of radiation damage, however, this can hamper the measurement due to the Debye Waller factor (probability of MS transition). In some cases, the interesting material physics are at low temperature, such as magnetic interactions.

For the first time since the 1980's we have applied so-called quenching experiments with short lived isotopes (~minutes), i.e. implantation at elevated temperatures (>300 K), while the measurement is performed at low temperature (77 K). In my presentation I will discuss some of the physics involved in connection with our new proposals. In addition, the data obtained from quenching experiments

in the 1980's will be revisited. Finally some of the new data acquired at the 2014 beam-time will be presented followed by a discussion of future possibilities.

Solid State Physics / **47**

Lattice location and thermal stability of Mn in ferromagnetic (Ga,Mn)As

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Mn-doped GaAs, or (Ga,Mn)As, has become the model system in which to explore the physics of carrier-mediated ferromagnetism in semiconductors and the associated spintronic phenomena [1]. In particular, as the most widely studied dilute magnetic semiconductors (DMS), (Ga,Mn)As is an ideal example of how the magnetic behavior of DMS materials is strongly influenced by the lattice sites occupied by the magnetic dopants [1].
We present emission channeling experiments performed at the EC-SLI setup on the lattice location of radioactive ⁵⁶Mn</sup> (t_{1/2} = 2.56 h) implanted into (Ga,Mn)As thin films. We show that the tetrahedral interstitial site with four As nearest neighbors (T_{As}) is the energetically favorable site regardless of the interstitial Mn atom being isolated or forming complexes with substitutional Mn. Furthermore, we show that the thermal stability of both substitutional and interstitial Mn, with respect to diffusion and segregation, strongly decreases with increasing Mn concentration (within the several % Mn regime). We discuss the implications of these findings on the understanding of Mn self-compensation in (Ga,Mn)As, and introduce the ongoing emission channeling experiments on the wider class of Mn-doped III-V DMS systems.

[1] T. Dietl and H. Ohno, *Rev. Mod. Phys.* **86**, 187 (2014).

Coulomb Excitation and Reactions / **27**

Direct reactions with exotic nuclei and projects at HIE-ISOLDE

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Direct reactions in inverse kinematics at low energies are essential tools to study the shell structure of unstable nuclei. Transfer reactions allow to determine the distribution of the spectroscopic strength,

necessary to investigate the shell evolution across the nuclear landscape. Proton-induced elastic and inelastic scattering give access to unique information about collectivity and matter radius.

A brief overview of current direct reaction programs with exotic nuclei worldwide will be given as well as the related technical developments. Possible new developments and studies in this field at ISOLDE and HIE-ISOLDE will discussed.

Coulomb Excitation and Reactions / 22

Shape Coexistence in ^{100}Zr Studied by Low-energy Coulomb Excitation

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The region surrounding the neutron number N = 60 for the Sr and Zr isotopic chains is an interesting example of shape evolution. Starting from the N = 50 closed spherical shell, and removing a few neutrons, the Sr and Zr isotopes become well deformed. On the neutron-rich side of these isotopic chains, N = 56 is observed to become an effective sub-shell closure with ^{96}Zr exhibiting the properties of a doubly-magic nucleus. However, with the addition of only four more neutrons, ^{100}Zr is observed to become strongly deformed. This sudden change from a spherical shape to one with large deformation, which is also observed for neighbouring N = 60 isotones such as ^{98}Sr, has attracted many theoretical and experimental investigations over several decades and is probably the most sudden change from a spherical shape to one with large deformation of known nuclei. A stringent analysis of the nuclear structure and intrinsic shape of the nucleus ^{100}Zr is, therefore, imperative. In order to shed new light on this phenomenon a Coulomb excitation experiment was performed with the aim of measuring reduced transition probabilities between low-lying excited states and quadrupole moments in order to determine the states'intrinsic shapes.

The ^{100}Zr beam was provided by the Californium Rare Isotope Breeder Upgrade (CARIBU) system, the only facility able to deliver intense beams of refractory elements such as zirconium. De-excitation γ-rays were detected with GRETINA detector array with the CHICO2 particle detector array employed for the detection of ^{100}Zr projectiles and recoiling target nuclei. In this presentation, an overview of the recently performed experiment will be given and initial results presented.

Coulomb Excitation and Reactions / 59

Nuclear structure studies of neutron-rich Rb isotopes using Coulomb excitation

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The neutron-rich A=100 mass region has recently risen up a high interest of the nuclear structure community. When going from N=58 to N=60, a rapid shape transition occurs from spherical to well deformed ground state shape, similar to what is observed in the rare earths region. This region firstly

accessible by fission [1] has been later studied by mass and laser spectroscopy (e.g. [2]), which highlighted the presence of deformation at N˜60. According to recent mass [3] and Coulomb excitation [4] measurements, the Kr isotopic chain presents a more gradual evolution of deformation. Since the Rb isotopic chain is placed at the low-Z border of deformation region, it constitutes a good candidate to identify and characterize the mechanisms involved in the development of deformation.

Excited states in ^{93,95,97,99}Rb were populated via low-energy Coulomb excitation. The nuclei of interest were produced at ISOLDE (CERN) using a UCx target. The beam is post-accelerated up to 2.83 MeV/u using REX-ISOLDE and then impinges on a secondary target of ^{60}Ni positioned in the centre of the MiniBall array used for particle and gamma-ray detection.

Excited states in ^{97,99}Rb were observed for the first time in this study. Level schemes have been constructed by analysing gamma-gamma matrices, which show a clear rotational character in contrast to what is observed for the spherical-like ^{93,95}Rb isotopes. It validates the scenario of a rapid shape transition at N=60, which is also confirmed by the transition probabilities extracted from this dataset using the GOSIA code (see abstract of M. Zielinska *et al.*).

The particle-rotor model constitutes an appropriated tool to interpret the level scheme as rotational bands. By comparing experimental and theoretical values from a quasi-particle model of the B(M1)/B(E2) ratios and g-factor, a firmed assignment of the $3/2^{+}[431]$ Nilsson orbital as the ground state configuration of the ^{97}Rb has been determined.

[1] S.A.E Johansson *et al.*, Nuclear Physics 64, p. 147-160 (1965)

[2] C. Thibault *et al.*, Phys. Rev. C 23, 2720 (1981).

[3] S. Naimi *et al.*, Phys. Rev. Lett. 105, 032502, (2010).

[4] M. Albers *et al.*, Phys. Rev. Lett. 108, 062701 (2012).

Coulomb Excitation and Reactions / 64

In trap polarization of radioactive ion beams

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In this contribution we discuss the potentials of a new technique of optical orientation of radioactive ions trapped in an open Paul trap, permitting to reach a very high degree of polarization, for beta decay experiments.

More precisely, laser polarization of the alkali-earth ions 23Mg+ and 39Ca+ in a Paul trap and detection of the emitted electron and recoil ion shall enable the measurement of the so-called D correlation. D is a triple correlation of the form <**J**> (**pe** x **pnu**) with pe and pnu being the momenta of the electron and the neutrino, and J the nuclear spin. The D correlation violates Time reversal. While such violation is predicted to occur in the Standard Model via the quark mixing mechanism, experimental constraints are 5 to 10 orders of magnitude lower [1].There is a large window in which D, R correlations and neutron EDM searches can contribute to the search for other sources of CP violation at a much higher level, which could explain for example the large matter-antimatter asymmetry observed in the universe. The best constraints so far on D arise from the neutron decay and are of the order of 2×10-4 on coupling constants of interactions violating T [2]. Lower constraints have been obtained from hyperon, Kaon, and nuclear decays. The latter were derived from the decay of 19Ne yielding a constraint of 6×10-4, limited by statistics [3]. With the expected rates from the upgraded SPIRAL facility at GANIL, an experiment aiming at D-correlation measurement with an unprecedented sensitivity of the order of 10-4 can be conceived. It is envisaged to perform a proof-of-principle of the laser polarization method at ISOLDE, using the COLLAPS laser setup, together with an optimized trapping setup inspired by the one of LPCTrap [4].

[1]: G. Ban et al., Nucl. Phys. A 827, 422c (2009)

[2]: J. Beringer et al, (Particle Data Group) Phys. Rev. D 86 (2012) 010001

[3]: F. P. Calaprice, Hyp. Interact. 22 (1985) 83

[4]: G. Ban et al, Ann. Phys. (Berlin) 525(2013)576

Ground States and Decays / 46

Study of Gamow Teller transitions using beta decay and charge exchange reactions

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The study of the properties of nuclei far from stability is one of the main frontiers of modern nuclear physics.
Among many possible observables for nuclear structure, the β decay strengths provide important testing grounds for nuclear structure theories far from stability. The mechanism of β decay is well understood and dominated by allowed Fermi (F) and Gamow-Teller (GT) transitions. A successful description of the nuclear structure of the states involved should provide good predictions for the corresponding transition strengths B(F) and B(GT).

Gamow-Teller and Fermi transitions can be studied in two different ways,
namely in β decay mediated by the weak interaction and
in charge exchange(CE) reactions where the strong interaction is
involved.
The β decay has an advantage in that it provides absolute B(GT)
values, the GT transition strengths,
but is limited by the energy window available.
In contrast, CE reactions provide only relative B(GT) values,
but there are no restrictions on the accessible excitation energy in the final nucleus.

An alternative approach is to assume isospin symmetry and to compare
β decay and CE reactions in mirror nuclei.
%
Assuming the same GT response in mirror transitions,
one can combine β and CE to produce
a complete picture of the GT strengths in both mirror nuclei.
This is possible when the proton-rich nucleus β decays and the neutron-rich nucleus provides a stable target.

In this talk I will concentrate on two β studies carried out at fragmentation facilities, the first one was carried out at GSI on $T_z = -1$ nuclei and
the second beta-decay at GANIL on the $T_z = -2$ nucleus ^{56}Zn. In both cases the results will be compared with the mirror CE reactions performed at RCNP. In the case of ^{56}Zn a very exotic decay mode at the proton drip-line, β-delayed γ-proton decay, has been observed. This result will be discussed in detail.

Ground States and Decays / 45

Hyperfine structure studies of At isotopes using in-source laser spectroscopy at 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 the Z=82 shell closure [1], while on the neutron-rich side effects due to octupole deformation could be important. In order to determine the extent to which the ground and isomeric states of these nuclides are affected by these phenomena, an extended campaign of investigation of changes in the mean-square charge radii is being conducted at ISOLDE by the Windmill Collaboration. The measurements rely on the high sensitivity provided by a combination of the in-source laser spectroscopy with RILIS, ISOLDE mass separation and Windmill spectroscopy setup [2].

During the September 2014 IS534-III experiment, a collaborative effort was made by the RILIS [3], ISOLTRAP [4] and Windmill teams to investigate HFS/IS in a long chain of isotopes ranging from 194At to 219At (Z=85, N=109-134) [5]. These isotopes span from the region of expected deformation near the neutron mid-shell at N=104, across the spherical region at N=126, before reaching an area of predicted octupole deformation at N=132. In this contribution, we will present the systematics of the charge radii obtained from this isotopic chain.

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[5] A.N. Andreyev, A. E. Barzakh, V. N. Fedosseev, P. Van Duppen et al., IS534-III experiment at ISOLDE (Sep 2014)

*On behalf of ISOLTRAP –RILIS –Windmill –Bratislava-Leuven-Gatchina-ISOLDE-Mainz-Manchester-York Collaboration

Ground States and Decays / 61

Study of multi-neutron emission in the beta-decay of 11Li

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Beta-decay spectroscopy is one of the most important tools for the study of nuclear structure. In exotic nuclei beta-decay can often be followed by the emission of delayed particles, a process which becomes the dominant decay channel when approaching the driplines. In the most exotic species, the emission of two or more delayed particles can also occur with a significant probability.

Whereas two delayed proton spectroscopy has been performed in a number of cases, no spectroscopic study of two delayed neutron emission, with measurement of the neutron energies and angles, has been undertaken.

We performed an experiment at ISOLDE in October 2014 to detect for the first time in coincidence two delayed neutrons from the decay of 11Li and measure their energies and angles, in order to study the sequential or direct character of the emission and the possible correlations between the neutrons.

This experiment used an array of liquid scintillator modules coupled to a digital electronics and signal processing system for the detection of neutrons. The use of liquid scintillator allows to perform neutron-gamma discrimination to suppress random coincidences involving background.

This talk will present the aim of this experiment, the analysis techniques and the status of the data analysis.

Ground States and Decays / 14

Study of the ^{129}Sn structure by beta decay: On the nature of the $3/2^+$ ground state and $1/2^+$ 315.3-keV level

Authors: Angela Gargano[1]; Henryk Mach[2]; Razvan Lica[3]

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We have investigated levels in ^{129}Sn populated from the β^- decay of ^{129}In isomers at the ISOLDE facility.
The ^{129}Sn nucleus is a three-neutron hole system next to the doubly magic ^{132}Sn.
The involved states of spin $1/2^+$ and $3/2^+$ are expected to have a configuration determined by the neutron $s_{1/2}$ and $d_{3/2}$ single particle states, respectively. Consequently, these states should be connected by a rather slow l-forbidden M1 transition.
Using the fast timing technique we have measured the lifetime of the $1/2^+$ 315.3-keV level and determined the transition rate for the 315.3-keV γ-ray feeding the $3/2^+$ ground state.
Our measurement shows a moderately fast M1 transition with a very weak,
if any, E2 component.
The previously reported level schemes in ^{129}Sn were mostly confirmed by the $\gamma - \gamma$ coincidences.
This study represents the first test of the ISOLDE Decay Station (IDS).

Ground States and Decays / 37

Estimation of production rates and secondary beam intensities

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Summary of the work, performed as a part of the project Eurisol Design Study, will be presented and possibilities for further activities at the HIE-ISOLDE will be discussed. As a part of the Eurisol Design Study, dedicated task Beam Intensity Calculation focused on possibilities to predict achievable secondary beam intensities at the ISOL facility using the spallation reaction. Model calculations were performed and the results were compared to available data. Successful calculations allow to estimate production of exotic nuclei in the target and thus offer possibilities for study of the mechanism of the transport of such nuclei out of the target. Possibilities to continue this work in systematic way at ISOLDE will be discussed.

Ground States and Decays / **42**

Results from the recent 207Tl experiment using the ISOLDE Decay Station with triggerless data acquisition.

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Results from the recent 207Tl experiment using the ISOLDE Decay Station
with triggerless data acquisition.

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A recent experiment was performed using the ISOLDE Decay Station to measure low-lying states in 207Tl populated via the β decay of 207Hg, produced using a molten lead target. The 207Tl nucleus has one proton less than 208Pb, which is a classic shell model core. Above the lowest-lying states, structure is likely based on the coupling of the proton hole to either a broken proton or neutron pair, which would require excitation across a shell closure, or to a collective octupole excitation. The observation of these states will reveal information on the single-particle orbitals near the shell closures at Z = 82 and N = 126, which will be valuable for the improvement of the predictive power of nuclear models.

An additional objective of the experiment was to test the feasibility of producing a 208Hg beam from a molten lead target with the intention of studying states in 208Tl populated via the β decay of 208Hg. Such a study is crucial for the understanding of the proton-hole neutron-particle interactions in this region as information is scarce.

The ISOLDE Decay Station consisted of a four HPGe Clover detectors and a MINIBALL cluster for high-resolution γ-ray spectroscopy, in addition to three plastic scintillator detectors for observing radioactive β-decay events. Beams of 207Hg and 208Hg were implanted onto a tape from which subsequent radioactive decays could be observed. Data were recording using a triggerless data acquisition system in which every signal was recorded with a time stamp, enabling coincident signals to be correlated in software.

Preliminary results from the early analysis of this experiment, showing many promising new γ rays associated with 207Tl, will be presented for both the 207Tl and 208Tl objectives.

Facilities and Instruments / 1

The iThemba LABS Facility: Coulomb excitation studies and future plans at HIE-ISOLDE

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HIE-ISOLDE will revolutionize the scientific outcome of muti-step Coulomb excitation and reorientation effect measurements. Particularly, in reorientation effect measurements, the magnitude and sign of the diagonal matrix element for the first 2+ excitation in even-even nuclei will be determined with a higher degree of precision, which will improve our current understanding of phenomena such as shape coexistence, prolate vs oblate shapes, surface vibrations or how nuclei rotate. Nonetheless, RIB facilities are generally deficient delivering high-intensity beams and higher-lying states may be difficult to populate using Coulomb-excitation reactions. This is the case, for example, of establishing shape coexistence by determining the spectroscopic quadrupole moment of the second 2+ state in many nuclei (e.g., CERN-INTC-2012-067, INTC-P-368).

Additional reorientation-effect measurements with stable ion beams have been carried out at iThemba LABS. A flexible chamber for particle-gamma coincidence measurements has been constructed and the pipe-line for Coulomb-excitation measurements (S3 detectors, electronics, feedthroughs, etc) finalized. The first experiments ran successfully last November-December 2013. Moreover, a new funding application for an array of 16 clover HPGe detectors (GAMKA) has been submitted to the National Research Foundation, which would allow angular distribution measurements. New exotic stable beams are also being developed at iThemba LABS using organometallic chemistry, which will allow the study of novel reorientation-effect measurements. These measurements with stable beams at iThemba LABS will prepare our students with hands-on and data-analysis skills for similar RIB measurements as well as complementing the physics case at HIE-ISOLDE. Coulomb excitation studies and supportive measurements at iThemba LABS, that will support the HIE-ISOLDE program, will be presented. Moreover, the prospect of a RIB facility at iThemba LABS is a strong motivation to strengthen our research program at HIE-ISOLDE.

Facilities and Instruments / 81

The ALTO Facility

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The ALTO facility consists in two accelerators within the same installation. A Tandem accelerator dedicated to stable (ions and cluster) beam and a linear electron accelerator dedicated to the production of radioactive beams. The ALTO facility can deliver radioactive beams, stable beams and cluster beams having a large physics case from nuclear structure to atomic physics, cluster physics, biology and nano-technology. A brief description of the facility will be given as well as of the on-going research program and future developments.

Facilities and Instruments / 9

The AGATA Array and Recent Results

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The Advanced GAmma Tracking Array is a next generation high-resolution gamma-ray spectrometer for nuclear structure studies based on the novel principle of gamma-ray tracking. It will be built from a novel type of high-fold segmented germanium detectors which will operate in position-sensitive mode by employing digital electronics and pulse-shape decomposition algorithms. AGATA is and will be employed at the leading infrastructures for nuclear structure studies in Europe. The first implementation of the array consisted of 5 AGATA modules; it was operated at INFN Legnaro. A larger array of AGATA modules was employed at the FRS focal plane at GSI for experiments with unstable ion beams at relativistic energies. The presentation will describe the novel gamma-ray tracking method. Examples of physics cases from the two different sites and the new spectrometer will be presented.

Facilities and Instruments / 80

Status of the HIE-ISOLDE Project

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After 20 years of successful ISOLDE operation at the PS-Booster, a major upgrade of the facility, the HIE-ISOLDE (High Intensity and Energy ISOLDE) project was launched in 2010. It is divided into three parts; a staged upgrade of the REX post-accelerator to increase the beam energy from 3.3 MeV/u to 10 MeV/u using a super-conducting Linac, an evaluation of the critical issues associated with an increase in proton-beam intensity and energy (increase from 1.4 GeV to 2 GeV) and a machine design for an improvement in RIB quality. The latter two will be addressed within the HIE-ISOLDE Design Study. This presentation aims to provide an overview of the present status of the overall project by providing; an insight to the infrastructure modifications, progress on the high beta Quarter Wave Resonant (QWR) cavities and cryomodule production as well as the installation of the HEBT lines.

Facilities and Instruments / 53

Results from the first tests with the SPEDE spectrometer

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Co-authors: Daniel Cox [2]; David Jenkins [3]; David Wells [2]; George Genghis O'Neill [4]; Janne Pakarinen [1]; Jim Thornhill [2]; Joonas Konki [5]; Kimmo Ranttila [5]; Mark L Huyse [6]; Panu Rahkila [5]; Paul Davies [3]; Paul Thomas Greenlees [5]; Peter Butler [4]; Piet Van Duppen [6]; Rolf-Dietmar Herzberg [7]; Ville-Pekka Saarela [5]

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The SPEDE spectrometer [1, 2] aims to combine a silicon detector, for the detection of electrons, with the MINIBALL γ-ray detection array for in-beam studies employing radioactive ion beams at the HIE-ISOLDE facility at CERN. SPEDE is one of the first attempts to combine in-beam γ-ray and conversion electron spectroscopy with radioactive ion beams.

The setup will be primarily used for octupole collectivity [3] and shape coexistence studies [4, 5] in Coulomb excitation experiments. In the shape coexistence cases the transitions between states of the same spin and parity have enhanced E0 strength [6]. Additionally the $0^+ \rightarrow 0^+$ transitions, typically present in nuclei exhibiting shape coexistence [7], can only occur via E0 transitions, i.e. via internal conversion electron emission. The simultaneous observation of both electrons and γ-rays is especially important for the analysis of multi-step Coulex data.

The concept of the SPEDE spectrometer was introduced for the ISOLDE community in the previous users meeting. In this presentation the finalized design of the spectrometer will be described together with results from the first tests.

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Special Topic / 11

Results from the LHC

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The LHC is the highest energy collider in the world, and has run successfully over recent years. The experiments at the LHC will be briefly reviewed, along with some of their key results from the first run. Particular focus will be made on the dedicated flavour-physics experiment LHCb, and prospects for the future run.

Golden Jubilee / 78

From pre-ISOLDE to ISOLDE: some personal recollections

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A constellation of special circumstances made the approval of ISOLDE possible, in spite of the main priority of CERN as an elementary particle physics laboratory. I have personally experienced some of these as a post-doc at CERN as will be briefly discussed.

Golden Jubilee / 19

From ISOLDE to ISOLDE 2

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On December 17, 1964 the CERN DG, Victor Weisskopf, sent a letter to the ISOLDE Collaboration giving green light to perform experiments at CERN. An underground hall was built close to the SC, which accelerated protons to 600MeV energy. The first experiment at ISOLDE was preformed on September 17, 1967. In my talk I shall cover the first years of experiments at ISOLDE at CERN, the SC Improvement Programme and the building of ISOLDE 2.

Golden Jubilee / 23

ISOLDE 1985-1987: In the shadow of LEP construction

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This report describes my time at CERN from 1985 to 1987. Only very briefly before, ISOLDE was recognized by the CERN Management as a CERN facility and not only as a collaboration performing experiments at the synchrocyclotron (SC). Due to LEP construction the human resources were extremely restricted and I acted in one person as ISOLDE Group Leader, as Coordinator of the Synchrocyclotron, and as person responsible for the ISOLDE Technical Group. In addition, I was responsible for the students of my research groups from Mainz University which were active in laser spectroscopy of neutron-deficient nuclides in the mercury region and in getting ISOLTRAP on the floor and into operation. Due to LEP construction also the financial resources were extremely limited and my requests to the EP Division Leader B. Hyams and to the Director General H. Schopper for financial support for installation of a laser ion source and ISOLTRAP were turned down. Still, I and my students had a lot of fun at ISOLDE and I am very happy that there are still some remains of my time at CERN: first of all ISOLTRAP, but also RILIS (which came into full swing only when ISOLDE was relocated at the PS Booster), or some traces back to the ISOLDE Users'Guide of 1986, or the weekly meetings of the ISOLDE Technical Group.

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Last 3 years of the SC-ISOLDE and move to PS-Booster

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In 1987 the very successful operation of ISOLDE-2 could be continued with an ever increasing number of users. The ISOLDE-3 facility was finished in 1988 and made available too, even in high-resolution mode. As it was evident that post-acceleration of the radioactive beams would be needed in the future, a first project with a series of linacs was forwarded.
It had been clear, however, that CERN could not support the SC operation in the long term. An envisaged transfer to the Rutherford-Appleton Lab did not materialize, primarily for financial reasons. Fortunately the CERN management agreed to support a move to the PS-Booster and preparations started immediately following this decision.
Thus in the years 1989 and 1990 a special effort was made to supply beam to as many research projects as possible, resulting in a record number of beam shifts from the ISOLDE separators. The collaboration even had to partially support the last year of SC running before the final shutdown in December 1990.

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1993-1995: the Pre REX-ISOLDE Era

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Soon after the commissioning of ISOLDE at the PS-Booster facility, first experiments took place. This contribution will discuss highlights from the 1993-1995 period with a special focus on the preparatory work for the proposal to post-accelerate the ISOLDE beams. This lead eventually to the approval of the "Radioactive beam EXperiments at ISOLDE: Coulomb excitation and neutron transfer reactions of exotic nuclei" proposal under IS347.

Golden Jubilee / 33

ISOLDE 1996-1999: Preparing for new science opportunities

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1996-1999 was a time in which ISOLDE saw important changes. In order to make space for REX-ISOLDE the experimental hall saw its first extension and first equipment for REX-ISOLDE was installed and commissioned.

Golden Jubilee / 39

ISOLDE at the turn of the millennium

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At the transition to the twenty first century ISOLDE was undergoing a major upgrade from a very successful low-energy radioactive ion beam facility towards a new era of nuclear structure studies employing accelerated radioactive beams [1]. The first accelerated beam was obtained in November 2001 when REX-ISOLDE produced a 2.2 MeV/u beam of 26Na ions. Additionally, the ISOLDE complex was made particularly attractive facility due to other break-through developments in the fields of laser ion sources and ion traps. Some highlights from the years 1999 to 2002 during my time as a group leader will be presented.

1. Juha Äystö, CERN's longest serving experimental facility, in Physics Reports 403 (2004) 459

Golden Jubilee / 2

ISOLDE: the Anglo-Saxon Era 2002-2005

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This presentation summarises the highlights at ISOLDE during my time as group leader 2002-2005

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The ISOLDE group 2005-2008

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In the years leading up to the first beams in LHC in the autumn 2008 most CERN efforts were focussed on finishing the LHC. Still, ISOLDE managed to evolve and broaden its physics scope. I shall give a brief overview of the main events taking place at ISOLDE in the period 2005-2008, including the consolidation of the existing infrastructure and the preparations for the HIE-ISOLDE project, and remind about some of the physics results coming out. I shall also mention the developments in and around the ISOLDE Collaboration.

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My time as Group Leader 2008-2012

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I will give some highlights about my time as ISOLDE Physics Group Leader from 2008 to 2012.

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Concluding Remarks

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Workshop Closing Comments

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Study on Diagnostic System for Quality Control of the HIE-ISOLDE Cavities.

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I will present on development of a diagnostic system for the HIE-ISOLDE accelerating cavity.
The HIE-ISOLDE cavity is a superconducting quater-wave resonator made of a copper substrate on which a niobium film of a few micron is sputtered.
Five cavities have been constructed for the first cryomodule by last November; however their performance is not always as good as a nominal value (Q-value of 5x10ˆ8, acceleration field of 6 MV/m).

A diagnostic system is required to study the cavity during RF measurement, localizing defects or seeing any other phenomena.
The system will be constructed with temperature sensors and magnetic flux sensors.
The effect of thermoelectric current will be also studied with the same system.
Basic ideas and current status will be shown.

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Features of mechanisms of nuclear interactions, structure and properties of weakly bound (exotic and cluster) nuclei at low energies.

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Design, development and production of new experimental techniques at ISOLDE to measure:
- Angular distributions of differential cross-sections (ADDCS) of elastic and inelastic scattering with high energy and angular resolution;
- Total reaction cross-sections (TRCS) and excitation functions.

Preliminary research to direct experiments:
- Conduction of control and test measurements of the new method, measurement of angular characteristics of the scattering chamber, energy and angular errors.

Experimental study of nuclear interactions (ADDCS of scattering, TRCS and excitation functions) with light, weakly bound (exotic and cluster) nuclei at low energies and high intensities –with optimal angular and energy resolution. Study of features of diffractive scattering of light exotic and cluster nuclei: possible manifestations of differences in the distribution of nucleons in these nuclei –at energies of Fraunhofer scattering.

Theoretical analysis (diffractive, optico-potential) of experimental data (ADDS of scattering, TRCS and excitation functions) within the interactions of light weakly bound nuclei.

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High-precision mass spectrometry of rare isotopes with ISOLTRAP

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ISOLTRAP is a state-of-the-art experiment at ISOLDE-CERN for Penning-trap mass spectrometry of short-lived nuclides [1, 2]. The Phase-Imaging Ion-Cyclotron-Resonance (PI-ICR) [3] technique, recently developed by SHIPTRAP at GSI, is a promising approach to gain precision and mass resolving power for Penning-trap spectrometers. Its use would lead to an enhancement in precision of a factor of 5 and in resolving power of a factor of 40, likewise to a decrease of the measurement time by a factor of 25 for achieving the same precision as the standard Time-of-Flight Ion-Cyclotron-Resonance (ToF-ICR) technique [3, 4]. The implementation of the PI-ICR technique at ISOLTRAP will potentially allow the study of exotic nuclear species with higher precision and within less measurement time than presently possible. To this end, a position-sensitive detector was recently assembled for off-line tests. Results of studies of the detector's characteristics will be presented, as well as preliminary investigations of the accuracy of ISOLTRAP for the implementation of the phase-imaging detection technique.

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Non-linear dependence of the electric field gradient on the AlN content x in AlxGa(1-x)N

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The ternary alloy systems based on AlN, GaN and InN are widely used in LEDs. The advantage is the continuous change in the bandgap that can be tailored by the alloy composition. Interestingly, the dependence of the bandgap on the constituents is not following Vegard's law which states that the lattice constants should change linear with the alloy content. But measurements show, that an additional bowing parameter has to be introduced to describe the dependence on the alloy contents. The electric field gradient (EFG) which is measured by the perturbed angular correlation method (PAC) depends on the c/a ratio of the lattice constants c and a of the Group III nitrides. So it is expected that the EFG follows Vegard's law as well and the question if the bowing parameter is correlated with the lattice constants can be addressed with PAC. Therefore the AlxGa(1-x)N system was studied at the ISOLDE facility. Samples with different AlN content x were implanted with the isotopes 111mCd and 117Cd. After the annealing of the implantation damage in flowing nitrogen PAC measurements were performed. The AlN molar fraction x was determined by Rutherford Backscattering experiments. The obtained results are compared to previous measurements with 111In and 181Hf. It can be shown that a bowing parameter has to be introduced to describe the dependence of AlN content and EFG in AlxGa(1-x)N. The bowing parameter depends on the implanted impurity which acts as PAC-Probe and interestingly not on temperature.

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ATOMIC LOCAL STUDIES ON GRAPHENE USING ISOLATED AD-ATOM PROBES

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The one-atom-thick crystal - graphene, uniquely combines many exotic properties such as huge mechanical strength with high electronic and thermal conductivities, among others, which make it interesting for fundamental physics and applications. Its properties strongly depend on surface and interface nanoscale interactions, where the physical models should apply aiming their understanding and control.

In the present work we aim investigating the mechanisms of adhesion of ad-atoms on the surface, their capture processes, adsorption and migration of atoms, alone or intermediated by water and defects. The later aim is to investigate electronic, magnetic and catalytic properties resulting from such "dopant"like interactions. Experimental works are accompanied by theory and computational models based on density functional theory, quite adequate for simulating the electronic properties and the hyperfine parameters which consist of our experimental observables, as measured with the nuclear spectroscopy Perturbed Angular Correlations (PAC) technique. PAC allows probing at the atomic scale the add-atoms interactions without interfering with the graphene electronic structure, thereby providing unique information. PAC measures the electric field gradient (EFG) that provides structural information, location of the probe, stability, and bond (ionic, covalent bonding, van der

Waals), and the magnetic hyperfine field (MHF) that translates properties correlated with the electronic spin configuration.
We will present some results of the PAC hyperfine parameters obtained in graphene grown at different substrates using199mHg as a probe. To complement the experimental studies, ab initio simulations, using the software Wien2k and VASP, with the self-consistent LAPW+lo and PAW methods to solve the Kohn-Sham equations and GGA/LDA approximations, have been implemented to simulate the charge density distribution of ad-atoms on graphene. This is the first step to attain the next objective that is to look for the bonding of isolated ad-atoms at the graphene surface there brought by soft landing (evaporation) of the radioactive probe under UHV ambient.

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Proton emission and low lying states in proton drip nuclei

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Measuring the proton emission decay widths and corroborating them with microscopic calculations have yielded rich information about the structure and decay properties of proton drip nuclei. The spectroscopic data on the low lying states of these nuclei are also crucial in complementing the information from decay widths. Apart from proton emitters, the spectroscopic data of low lying states of neighbouring nuclei are also useful in understanding the nuclear structure at this extreme. A few such cases where the data is scarce or not available will be pointed out and in such cases the importance of our recently proposed approach for rotation particle coupling will also be highlighted. The particle rotor model (PRM) is widely used and quite successful for a long time, in explaining the observed rotational spectra of several nuclei [1,2]. Microscopic theories for proton emission utilizing this approach is regarded as one among the most robust and successful approaches [3,4]. We propose a formalism named as the coupling matrix approach with which the deviation from the rotational behaviour of the core can be taken in to account properly. The key idea of this formalism is based on the coupled channels approach for odd-even nuclei suggested in Refs. [1,5] and was successfully applied to study the nucleus 151Lu [6]. Extension of this method to odd-odd nuclei and application to proton emitters will be discussed in the workshop.

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Recent results and perspectives using T-REX with MINIBALL

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T-REX is a large acceptance silicon array which is coupled to MINIBALL at ISOLDE. Its main purpose it to measure angular distributions of emitted light particles after transfer reactions, allowing to quantify the shell model configurations of excited single particle states or collective excitations in exotic nuclei.

Recently, T-REX was re-designed to also allow for Coulomb-Excitation experiments. The large angular coverage allows for a precise determination of quadrupole moments and allows for a reliable determination of matrix elements after multistep coulomb excitation. We present latest results from our high-intensity 72Zn multiple Coulomb excitation experiment at ISOLDE, resulting e.g. in a precise value for the quadrupole moment of the first 2+ state as well as in matrix elements connecting several low-lying states. We also populated the 0+2 state in this nucleus, who's collective properties may gain new insight into the complex shape coexistence phenomena around N=40.

Our collaboration is currently investigating a major upgrade of the T-REX array towards HIE-ISOLDE. Beside a substantial improvement of energy resolution, a combined setup for Coulomb Excitation experiments and direct nuclear reactions is under discussion. This also includes a new and uniform readout scheme for MINIBALL and auxiliary detectors. We give an overview of the current developments and challenges.

5

Breakup and transfer reactions with ^{7}Be to study ^{7}Li abundance anomaly

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The production and destruction processes of the ^{7}Be nucleus is of utmost importance
in studying the ^{7}Li abundance anomaly. Before invoking solutions beyond nuclear physics
the relevant reaction rates need to be measured with better accuracy. The production of ^{7}Be by the radiative capture reaction ^{3}He + ^{4}He $\rightarrow$ ^{7}Be + γ can be measured by the time reversed Coulomb breakup reaction of ^{7}Be, preferably in the presence of heavy targets. This would enable measurements at low relative breakup energies
(astrophysical energies) between the fragments, thereby extracting information about the required

radiative capture reaction. This avoids required extrapolation in the direct method from measurements performed at higher energies. On the other hand, the destruction of ^{7}Be through resonance excitation in the transfer reaction ^{7}Be(d,p)^{8}Be* deserves attention in the context of contradiction between theory and observation. Status on the preparation including simulation of the upcoming experiment at HIE-ISOLDE (IS 554) to study the ^{7}Be + d reaction will be discussed.

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Hg-coordination studies of several different types of small organic compounds by ^{199m}Hg-TDPAC

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Time differential perturbed angular correlation (TD-PAC) of γ-rays spectroscopy belongs to the family of spectroscopic techniques which allow for measurements of hyperfine interactions, and is a useful tool in the study of biomolecules [1,2], for example for the elucidation of how the function of a metalloprotein is related to the structure and dynamics of the metal ion binding site. In order to obtain empirical data correlating structure nuclear quadrupole parameters for Hg(II) containing compounds with biologically relevant ligands, we conducted ^{199m}Hg PAC experiments on a series of model compounds in 2007 and 2008 at ISOLDE-CERN. The aims of these experiments were to 1) use the empirical data in the interpretation of ^{199m}Hg PAC experiments on proteins, and 2) provide reference data for density functional and *ab initio* calculations of electric field gradients in Hg(II) complexes [3].

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Spectrometers for HIE-ISOLDE

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The higher beam energy, and improved beam qualities, that HIE-ISOLDE will offer opens the door to new possibilities for nuclear reaction studies at the facility. Simulation results for a mass separator device and a ray-tracing spectrometer for secondary reactions with post-accelerated beams will be presented. Realistic HIE-ISOLDE parameters are used as input to the simulations and a variety of reactions between radioactive beam and light target particles are presented. The simulation results are discussed in the context of some possible uses for such a device: Spectroscopy, reaction channel selection and tagging.

Furthermore, the impact of an future upgrade of the HRS on selected physics cases will be presented and discussed.

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Jahn-Teller distortions study in Sm(Nd)MnO3 Manganites

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Manganites and their exquisite electronic properties have been extensively studied in the last decade due to both fundamental interest and possible applications of colossal magnetoresistance, magnetocaloric and multiferroicc properties [1,2]. Additionally, low-cost AMnO₃ and doped manganites have shown promising results for catalysts solutions [3,4]. In these systems orbital occupancy of the metal ion, orbital order and the Jahn-Teller effect have a critical role on the macroscopic materials properties.

In this work we will present the evolution of the local Jahn-Teller distortion across the Jahn-Teller phase transition studied with perturbed angular correlation technique. The local single-phase scenario, where the electron density is regularly distributed around the Mn sites versos the phase separation picture, where fully Jahn-Teller distorted Mn³⁺O₆ octahedra coexist with regular Mn³⁺O₆ ones, will be discussed.

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Electronic dynamics and probe location in Ga2O3

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Transparent conductive oxides (TCOs) are widely studied today because of being electrically conductive while being optically transparent, which make them quite desirable for technological applications.
Among the TCOs family, gallium oxide (Ga2O3) has the widest band-gap, 4.8 eV, making it interesting for photonic applications working in the visible and UV wavelength region. Ga2O3 is an intrinsic n-type semiconductor, therefore the scientific community is actively searching for p-type doping candidates, such as Cd.
By measuring the local charge distribution the Perturbed Angular Correlation (PAC) technique allows the determination of the probes'atomic location and the impurity/dopant-host interactions. Additionally, being a time differential method, it can map the recombination of ionized and excited electronic states of the impurity/dopant in the material under study.
In the present work, we used such techniques to study nanostructures and powder pellets of Ga2O3 after implantation and diffusion of 111In/111Cd and 111mCd/111Cd where the location of Cd probes was identified. Then by combining γ–γ PAC with 111In, 111mCd and the e-γ PAC technique with 111mCd, we found the existence of long lived excited states at the Cd acceptor and, as well, a correlation of the electronic recombination after the 111In electron-capture decay with the carrier density and electron mobility in the material, as a function of temperature.
To validate the interpretation of the experimental results, today there are available powerful Density Functional, DFT, simulation methods via the implementation of different atomic local models and charge configurations, producing hyperfine parameters to be compared with the experimental data obtained with the PAC technique.
In this work we will present the resume of data, analysis and perspectives of combining the γ–γ and e-γ PAC technique to study electronic dynamics onto semiconductors and insulator materials.

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Development of high-resolution resonance ionization spectroscopy of exotic beams at CRIS

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The progress towards high-resolution laser spectroscopy at the Collinear Resonance Ionization Spectroscopy (CRIS) experiment will be presented. This high spectral resolution is necessary to access nuclear observables like the electrical quadrupole moment, the spin and the change in mean charge radii of e.g. the ground states and isomers of the neutron-rich Ga and Cu isotopes (IS571 and IS531). In order to understand how to minimize the linewidth of the resonance ionization spectra, simulations on the laser-atom interactions were performed and compared to experimental results.

First, the theoretical framework underlying these simulations will be outlined. Additionally, experimental data obtained with stable beams of 39K will be shown, validating the theoretical simulations. These measurements were performed using a continuous-wave Ti:Sa laser in combination with a Pockels cell external to the laser cavity. During these offline tests, the FWHM of the hyperfine spectra could be reduced to ˜50 MHz in the CRIS geometry. Finally, the implications of these results on the exotic beam program of CRIS will be discussed.

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DFT calculations of hyperfine parameters of Fe-doped MgO

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Emission Mossbauer spectroscopy using the radioactive probe ^{57}Mn $\rightarrow$ ^{57}Fe has been performed by the Mossbauer Collaboration at ISOLDE. Among the materials studied have been semiconductors such as MgO, ZnO which are potentially interesting for dilute magnetism [1-4].

In order to better interpret experimental results, hyperfine parameters were obtained using first principle calculations in the frame work of density functional theory (DFT) and the full potential linearized augmented plane wave method (FP-LAPW) [5]. Various implantation sites were proposed and studied using two different approximations: Pedrew-Burke-Ernzerhof (PBE) and the PBE+U with a Hubbard-like coulomb term [6]. The Fe2+ state resulting from damage can be described by considering the effect of Coulomb correlations (U) in the oxygen p-band in addition to the correlation in the d-shell of the transition metal (Fe). We find that our calculations show good agreement with experimental results.

Finally, a discussion on density of state and electrical properties of Fe-doped MgO will be presented. This work demonstrates the benefit of ab initio calculations in helping to resolve outstanding questions arising from experiment.

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Collinear laser spectroscopy on neutron-rich Mn isotopes approaching $N = 40$

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The region below ^{68}Ni ($Z = 28$, $N = 40$) is characterized by a rapid shell structure evolution. In the neutron-rich Mn ($Z = 25$) isotopes, this results in an interesting interplay between single-particle and collective behavior. The $^{51,53-64}$Mn ground states as well as the ^{58,60,62}Mn isomeric states are studied via bunched beam collinear laser spectroscopy at ISOLDE. The measured hyperfine spectra allow for a model-independent extraction of the nuclear structure information. Firm spin assignments are made which is indispensable for constructing reliable level schemes in this mass region. In addition, the g-factors are determined so precisely that even small deviations from the trend can be observed. These deviations provide important information to understand the changing structure towards $N = 40$.

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Evaluated experimental IAS masses in NUBASE and the AME, the IMME coefficients and key measurements

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Isobaric Analog States (IAS) of ground state nuclei have been evaluated for the first time as part of the Atomic Mass Evaluation (AME). These states in light- to medium-weight nuclei are of interest in several areas of fundamental physics. Here we focus on mass modelling, with the determination of the Coulomb energy component which, in turn, allows us to test Wigner's Isobaric Multiplet Mass Equation (IMME). Experimental IAS masses have been evaluated for isospin multiplets T=1/2 to T=3 for masses A=8 to A=60 and the corresponding IMME coefficients extracted. These new results lead to a clearer and more precise view of the isospin dependence of nuclear mass for nuclides around N=Z.
The overall tendencies observed for this first complete evaluation will be presented, and the impact on current experimental and theoretical research considered.

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Neutron-rich nuclei and the low-energy enhancement of the photon strength function*

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As excitation energy increases towards the particle separation energy, the level density increases rapidly, creating the quasi-continuum. Nuclear properties in this excitation energy region are best characterized using statistical quantities, such as the photon strength function (PSF) which is the ability of atomic nuclei to emit and absorb photons.
For several Fe isotopes an unexpected increase in the PSF has been observed [1] for which the probability to decay with low energy gamma-rays was found to be more than an order of magnitude larger than predicted by theories. Similar observations have since been reported in other isotopes across the nuclear chart.
The enhancement of low energy gamma-ray emission is controversial since it changes our view of how the nucleus emits gamma-rays in the region of high level density. No conclusive theoretical results exist which can reproduce or explain these experimental observations although different models suggest that the low-energy enhancement may be due to: 1) transitions within the single particle continuum producing E1 radiation [2], and 2) a reorientation of the spins of high-j neutron and proton orbits producing M1 transitions [3].
Although, the underlying mechanism remains largely unexplored and unknown the enhancement has nonetheless a dramatic impact on elemental formation in the universe. It has been shown that this modification to the low energy part of the PSF can have order of magnitude effects on the neutron capture rates of very neutron-rich nuclei which lie in the r-process path [4].
Unfortunately, our knowledge of the PSF comes exclusively from measurements using stable beams and targets which is then extrapolated to the neutron-rich regime where r-process nucleosynthesis takes place. Low-energy PSF measurements have never been performed in nucleonic systems with very asymmetric proton to neutron ratios and the persistence of the enhancement is only based on assumptions. Measurements in the neutron-rich regime are not only of fundamental interest to nuclear physics research but have wide reaching consequences in the field of nuclear astrophysics.
In light of many open questions and their importance, a proposal has been submitted and was subsequently accepted by the INTC to run an HIE-ISOLDE experiment on 66,68Ni and investigating statistical decay properties of these nuclei.
In this talk I will give an overview of the current status on our understanding of the low-energy part of the PSF, its impact on nucleosynthesis, and discuss our plans to measure the PSF at HIE-ISOLDE.

*Supported by the National Research Foundation of South Africa.

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Is Classical Chemistry Relevant for Converter Targets?

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Is Classical Chemistry Relevant for Converter Targets?

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The inventory of the radionuclides produced in 1.4 GeV proton irradiated lead bismuth (LBE) targets has been indicated in our recent publication [1]. Quantitative analysis shows that huge amount of radioisotopes are produced in the LBE target, fair enough for clinical and other applications provided the desired activity is separated from the bulk target. Further, the results from Tall et al [2] shows possibility of production of At and Po radionuclides through secondary particle reactions in very thick LBE targets when bombarded with 1.4 GeV proton beam.

We have simulated this condition by irradiating thin LBE target with 50 MeV alpha particles in Variable Energy Cyclotron Centre, Kolkata, India. 210-At and 207-Po radionuclides were detected in the matrix. The aim of the experiment was to develop radiochemical method for separation of At radionuclides from bulk lead and bismuth targets and from the radiotoxic polonium radionuclides. The target was dissolved in HNO3, followed by spiking of 200,203-Pb and 204-Bi radionuclides to monitor the fate of the bulk in the radiochemical processes. It has been found that simple precipitation technique shows quantitative separation of At radionuclides from the bulk targets as well as from polonium radionuclides. The precipitation experiment was carried out by addition of (i) NH3 (ii) oxalic acid and (iii) K2Cr2O7 of which K2Cr2O7 was found to be most effective. Bulk Pb and Bi and 207-Po were quantitatively precipitated leaving >70% At radionuclides in the supernatant.

The developed separation procedure is simple, environment friendly and applicable for in-vivo use as there is no possibility for organic residue in the final product.

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Structure of 68Ni: new insights on the low-lying 0+ and 2+ states from two-neutron transfer on 66Ni and beta-decay of 68Co

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The region around the nucleus 68Ni, with a shell closure at Z = 28 and a sub-shell closure at N = 40, is the source of considerable interest in nuclear-structure studies. Despite a significant set of experimental and theoretical information available on 68Ni [1-5], the origin of its structure is still being questioned. A recent clarification of the energy and spin assignment of several low-lying 0+ and 2+ states [6-9] and state-of-the-art shell model calculations [5,10] hinted to the possibility of triple shape coexistence and highlighted the need of additional experimental investigation.

To better understand the structure of 68Ni, two complementary experiments: the two-neutron transfer reactions on 66Ni at 2.85 MeV/u and the beta-decay of 68Co were performed at ISOLDE.

On one hand, the 66Ni(t,p)68Ni reaction represents a unique tool to probe the nature of 0+ states in 68Ni. Coincidences between the outgoing light charged particles and gamma-rays were detected using the combined MINIBALL [11] gamma-ray spectrometer and the T-REX particle detection array [12]. Results of such coincidence analysis together with the reconstruction of angular distributions of the reaction products, revealing the most populated states, will be presented. An interpretation based on calculations within the Distorted-Wave Born Approximation (DWBA) and shell model two-nucleon amplitudes will be discussed.

On the other hand, the measurement of the beta-decay of the low spin isomer in 68Co selectively produced in the decay chain of 68Mn allowed us to build a revised decay scheme to 68Ni based on the clear identification of beta-gamma-E0 delayed coincidences. A strong emphasis will be put on the connections between the three lowest lying 0+ and 2+ determined from observed transitions and upper limits.

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High current measurements at TWINEBIS

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The TWINEBIS is a replica of REXEBIS used for off-line research and development. REXEBIS is designed to provide a stable 500 mA electron beam at an electron energy of approximately 6.5 keV. During long term operation the REXEBIS is typically run only at 200 mA for reliability purposes. The full design value operation was never used in practice.
Recently the first 500 mA electron beam was achieved at TWINEBIS under quasi-stable operation conditions. For the first time active focusing of the electron gun was used and demonstrated a major influence on the loss current and related non-thermal outgassing. The 500 mA current was achieved at higher than normal cathode temperature providing sufficient thermionic emission and stay close to space-charge limited operation. Such high cathode temperatures shorten the cathode life-time significantly, but also allow first experiments of optimizing the TWINEBIS for high-current electron beams.
The increased current affects the EBIS performance in several ways. First, owing to the increased current the EBIS acceptance and capacity will grow proportional to the current, however the same is true for the emittance. Furthermore the current density will increase linearly with the current,

which means reduced breeding time by a factor of 2.5.
The experiments were backed up by 2D and initial 3D simulations. The simulations provide better understanding of several operational aspects of the EBIS, such as the influence of radial symmetry-breaking misalignment on the loss current. The experiments will be continued with an IrCe cathode having a lower work function and longer life-time than the presently used LaB6 cathode.

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Lattice location of implanted 56Mn in 3C-SiC

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SiC is a wide band gap semiconductor with an increasing number of applications in high-temperature electronics. Similar to Si, transition metals (TMs) in SiC are the source of deep levels in the band gap, however, the knowledge on structural properties of TMs in SiC, such as possible lattice sites, is much less advanced.
In this work we report first results on the lattice site location of implanted 56Mn (2.58 h) in single-crystalline cubic (3C)-SiC, evaluated by means of the emission channelling effect. Following 40 keV low-fluence (10ˆ13 cmˆ-2) ion implantation, the ⊠⊠ emission patterns from 56Mn implanted samples were measured with a position-sensitive electron detector around the <100>, <111>, <110> and <211> crystallographic directions. All measurements were performed at room temperature, starting with the as-implanted state and following 10 minute isochronal annealing steps up to 900 °C in vacuum. While the data analysis is still in progress, so far we clearly identify Mn atoms located on three different lattice sites. In the as-implanted state, a fraction of 56Mn sits on tetrahedral interstitial sites with C atoms as nearest neighbours (TC). The second fraction is located near substitutional Si sites (SSi), roughly 0.05-0.20 Å away from the ideal SSi and ideal split$^{<100>}$ SPSi sites. The third fraction of Mn identified is sitting at bond-center C-Si (BC) sites.
Upon annealing up to 400℃ the Mn atoms sitting at BC sites move towards SC sites, whereas the Mn atoms located at TC interstitial positions do not move away.
At 500℃ annealing a decrease in the number of Mn at interstitial sites became obvious, however, this is not accompanied by the corresponding increase in the amount of Mn on substitutional sites. At annealing temperatures of 700°C and above a decrease in the number of Mn at substitutional sites is observed. Although the analysis of the experimental data is on-going, it is already clear that no more than three sites play a relevant role in this system.