Recent results from the DESPEC campaign at GSI

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Abstract. HISPES-DESPEC is a collaboration, part of NUSTAR, aiming at studying the structure of nuclei produced by projectile fragmentation reactions exploiting the beams delivered by the accelerator system at present and future facilities GSI and FAIR. In the early stages of the experimental activity at FAIR Phase-0, started in 2020, the collaboration focused the attention on studies following the decay of long-living isomeric states and $\beta$-decays with lifetimes in the millisecond-to-second range. A description of the set-up and of first results obtained in the experimental campaigns covering years 2020-2022 are the subject of this talk.

1 Introduction

The HISPEC-DESPEC (H/D) collaboration, part of the NUSTAR research program, exploits the actual and future high energy and intensity beams delivered by the GSI-FAIR accelerator complex, with two main approaches: HISPES (High-resolution In-flight SPECTroscopy) aims at performing detailed spectroscopic studies by measuring outgoing $\gamma$ radiation via nuclear and Coulomb excitation techniques, while DESPEC (DEcay SPECtroscopy) experiments aim at a detailed study of the decay mechanism in the most exotic nuclear species at reach at GSI-FAIR, thanks to the measurement of decay half-lives, competing decay modes and isomeric states. The core of the HISPEC setup is the Advanced GAmma Tracking Array (AGATA) \cite{1}, latest generation array of segmented HPGe detectors, able to reconstruct the initial energy of the emitted $\gamma$ radiation also in case of large Doppler displacement. To track the secondary reaction products AGATA is coupled to the LYCCA (Lund York Cologne Calorimeter) array \cite{2}, based on time of flight (TOF), energy loss and total energy measurements, in conjunction with a magnetic spectrometer. Lifetimes of specific nuclear states can be measured using plunger devices, or the active detectors of the LISA project \cite{3}. For the DESPEC experimental program, ions are stopped in the Advanced Implantation Detector Array (AIDA) and their subsequent decays measured. AIDA is surrounded by a modular and compact high-resolution $\gamma$-detection array, Degas (DEspec Germanium Array Spectrometer), as well as the neutron arrays MONSTER (MOpular Neutron time of flight SpectromTer) and Beta-dELayEd Neutron detector (BELEN). In addition, the Decay Total Absorption Spectrometer (DTAS) and the FAst TIMing Array (FATIMA) can be employed.

At the restart of operations at the GSI-FAIR facility, the H/D collaboration initiated an experimental campaign exploiting mainly the DESPEC suite of detectors, with the aim of addressing the nuclear structure of exotic nuclei my means of isomeric and radioactive decays. The study of isomeric states and of the radioactive decays can provide the first glimpses of the internal structure via its $\gamma$-ray ‘fingerprints’. A systematic study of key experimental signatures, such as the energy of the first excited state and/or of the ratio of the excitation energies of the lowest-lying levels in even-even nuclei can, e.g., demonstrate the erosion of the established magic numbers or reveal the emergence of nuclear collective excitations.

The experimental campaign targeted several areas in the chart of nuclei, ranging from the p-rich nuclei south of $^{100}$Sn, the rare-earth region around $^{190}$W and the heavy systems above $^{208}$Pb.

The set-ups and experiments performed using the so-called Phase-0 campaign at the restart of the GSI-FAIR facility are described in these proceedings, together with an overview of future plans.

2 The DESPEC setup for the GSI-FAIR Phase-0 campaigns

The exotic nuclei under investigation are produced by fragmentation reaction of the relativistic beams, provided by the LINAC+SIS18 accelerator complex. The beams impinging onto a primary target of $^{9}$Be, located at the entrance of the FFragment Seprator (FRS) \cite{4}. The zero-degree spectrometer, FRS, is used to select and transport the ions of interest towards the final detection set-up, located, for the campaigns in 2020-2022, in the S4 area at the end of the FRS, corresponding to its 4th focal point. The separation is achieved thanks to the $Bp - \Delta E - Bp$ technique, where the analysing capabilities of FRS dipoles are coupled to energy losses in passive degraders, to select and focus the wanted species at the final focus.

Postion, time of flight (TOF) and energy loss in detectors located along the flying path in the intermediate and...
final focal planes of FRS, serve to reconstruct, on an event-by-event basis, the ions of interest [5].

During the Phase-0 campaign, several detector combinations have been commissioned and used. The common piece of instrumentation is the AIDA set-up, based on Double Sided Silicon Strip Detectors (DSSSD) characterised by a high degree of pixelation. Each unit is a 8×8 cm² DSSSD tile with thickness of 1 mm, composed of 128×128 strips (16384 pixels), with a 0.560 mm inter-strip pitch. The DSSSDs are purchased as single (8×8 cm²) or triple (24×8 cm²) wafers devices. AIDA is used both to detect the implantation of the energetic fragments, depositing energies up to several GeVs, and the particles resulting from the radioactive decay of the parent nucleus, on the MeV energy scale.

Thanks to the high degree of pixelation, one can define the position (X, Y, Z, depth) where the nucleus has been implanted, and correlate it to the subsequently emitted decay particles. The measurement of the time elapsed between the implantation and the decay returns the half-life of the radioactive decay itself, ranging between tens of ms to several tens of seconds.

In the Phase-0 campaign AIDA detectors were used in both the narrow (8 cm wide) and wide (24 cm) combinations, with detectors placed in a stack to cover a large implantation range. AIDA is sandwiched between plastic scintillator detectors, also capable of measuring implants and decay particles. The fast plastic detector, named βPlastic, consists of a tile of BC-400 scintillator material, covering the same area as the AIDA detectors readout by a series of SiPM glued to each side. The βPlast detectors work together with AIDA in order to identify ion-β correlations resulting in an overall efficiency of 12% for events implanted in AIDA and β particles released in both the DSSSD and the plastic detector. AIDA itself is measured to have an efficiency of 35% for ion-β correlations.

In order to get access to various experimental quantities, several detector set-ups have been deployed in the Phase-0 campaign.

A combination of high-resolution, high-efficiency HPGe detectors and the Fast TIMing Array (FATIMA) set-up of LaBr₃:Ce scintillators is used to measure the internal γ-deexcitation following internal deexcitation of the nuclei, while the DESPEC Beta Decay Total Absorption Gamma-Ray Spectrometer (DTAS) provides access to the full B(GT).

The DESPEC Germanium Array Spectrometer (DEGAS) high-resolution high-efficiency HPGe array exploits the EUROBALL Cluster detectors, rearranged into clusters of three detectors, so-called triple clusters. DEGAS is designed to cover an implantation area of about 24×8 cm², demanded by the wider focal plane of the Super-FRS at FAIR, and well suited for the S4 focal plane of the FRS. The on-board electronics includes low-noise pre-amplifiers with overload recovery, high-voltage generators, power management and temperature controls. GSI-made (FEBEX) modules have been successfully employed in the experimental campaign performed in 2020-2022. The digitizer data are used to obtain both energy and time information [6].

FATIMA is a modular system, where the detector number and size, as well as angular coverage, could be changed according to the needs of the experiment. In the standard configuration, it consists of 26 LaBr₃:Ce crystals with a diameter size of 1.5×2 inch² length. FATIMA can be used to determine lifetimes by measuring the time difference between two detected γ rays, or, alternatively, it can be used to measure lifetimes of excited states populated by β decay. Details of the implementation of the FATIMA set-up at GSI are described in Ref. [7, 8], while a further description of the DESPEC detectors implementation at GSI-FAIR is given in [9].

The high-resolution set-up here described can be replaced by the DESPEC Beta Decay Total Absorption Gamma-Ray Spectrometer (DTAS) [10–12]. A modular design based on NaI(Tl) scintillators was chosen to take advantage of the information on γ-ray cascade multiplicity in data analysis. Sixteen modules with crystal dimensions 15×15×25 cm³ constitute DTAS providing the following figures of merit: measured energy resolution of 6.0% at 1.33 MeV, measured time resolution of 10 ns, expected spectrometer efficiency (from MC simulations) 86% (total) and 58% (peak) at the 1.33 MeV ⁶⁰Co line.

Figure 1 shows, in the top panel, the layout of the HPGe+FATIMA high-resolution, while the bottom panel presents the coupling to the DTAS array, both realised and used in the Phase-0 campaign.

The experimental approach used in the campaign in 2020-2022 is well established, having the DESPEC collaboration a long tradition in such studies. Novelities and latest improvements are focused on advances in the detector set-up and the use of digital electronics. Specifically, the newly developed DESPEC array, based on the coupling of the AIDA highly-segmented Silicon array and the high-efficiency DEGAS HPGe array, provides a step forward in the study of decay radiation in a fragmentation facility. The high-granularity of the DSSSDs of AIDA allows to sustain a high-count rate, making it feasible to study several species at the same time, and reducing the background induced by non-correlated implantations. In the case of isomeric decay this is particularly important, since it allows to accept a higher number of incoming ions. The increased γ-detection efficiency provided by the DEGAS array allows to detect weak transitions and low-branching ratios from new weakly populated states. In addition, the improved efficiency helps to reconstruct level schemes by allowing the analysis of high-fold coincidences and improved particle-γ correlations.

With comparable primary beam intensities to previous years, the improved sensitivity of the DESPEC array allows to reach further out into new the proton and neutron rich isotopes, with the GSI-FAIR accelerator complex coupled to the FRS.

3 DESPEC Experimental Campaigns in 2020-2022

The DESPEC collaboration successfully commissioned the majority of its subsystem during the runs in 2020-2022,
Figure 1. Top Panel: High-resolution DESPEC set-up consisting of HPGe detectors (left side) and FATIMA ones (right side), as employed during the Phase-0 campaign in 2020-2021. Bottom Panel: DTAS implementation at S4 FRS focal plane.
performing a series of experiments using AIDA, FATIMA, DEGAS and DTAS, arranging them in various configurations.

In 2020 the collaboration completed an experiment approaching the heaviest N=Z nuclei by studying seniority and electromagnetic transition rates in \(^{94}\text{Pd}\), populated by fragmentation of a \(^{124}\text{Xe}\) beam. Thanks to the Fast-Timing technique, the E2 strength for the \(2^+ \rightarrow 0^+\), \(4^+ \rightarrow 2^+\) transitions were measured in \(^{94}\text{Ru}\), exhibiting a drastic enhancement of transition strength in comparison with pure-seniority predictions as well as standard shell model calculations in the fpg proton hole space with respect to doubly-magic \(^{100}\text{Sn}\). This anomalous behavior is ascribed to a subtle interference between the wave function of the lowest seniority, \(\nu=2\), \(J^\pi = 4^+\) state and that of a closely-lying \(\nu=4\) state, that exhibits partial dynamic symmetry, resulting in a quantum phase transition from the seniority conserved regime to a seniority mixed regime. Results of the successful measurement are published in Physics Review C Letters [13].

The FATIMA set-up was also employed during the campaign in 2021, where three experiments were performed, covering three different regions in the nuclide chart: the first experiment focused on shape evolution in the A∼190 region, in particular focusing on n-rich W isotopes. The second experiment performed a study of octupole deformation in the region of mass around A∼225, where little to no experimental information on the internal structure and half-lives is available. Further details are found in the talk by M. Polettini (this issue). The last experiment of the 2021 campaign focused on the \(^{100}\text{Sn}\) region with the aim of studying the isomeric states in the Cd chain and providing access to E2 strengths in n-poor Sn isotopes. In this last run the wide layout of AIDA, covering the full focal plane, was employed.

The two experiments, performed in the campaign in 2022, aimed at attacking the same region in the chart of nuclides, around N=126, accessing the isomeric and \(\beta\)-delayed \(\gamma\) transitions in Os, Ir and Au nuclei, via two complementary approaches, exploiting the high resolution of DEGAS HPGe detectors to study the detailed decay scheme, and the overall B(\(\gamma\)GT) response thanks to the total absorption spectroscopy made available by the DTAS scintillators.

The analysis of the collected data is on-going for all the mentioned runs, with preliminary results already presented at several conferences.

4 Future perspectives

After a short campaign at Riken (J), the FATIMA array will be back to GSI-FAIR in 2024, to be used together with the DEGAS and AIDA detectors, for additional experimental runs within the FAIR Phase-0 framework.

Beams from SIS18 will further increase in intensity and allow to continue map the neutron and proton rich sides of the chart of nuclides. Additional detection equipment, in particular for neutron detection, can be coupled to this array to further extend the experimental information at reach.

With the advent of Super-FRS, the DESPEC set-up, thanks to its easy installation and quick feedback on the populated nuclei, will be exploited to help in the commissioning phases.

Later, when SIS-100 beams will become available, the HISPEC-DESPEC collaboration will move to the HISPEC part of its experimental program, in particular exploiting the AGATA spectrometer.

The collaboration plans to exploit the DESPEC suite of detectors for campaign with first beams from SIS-100 and Super-FRS at the Early Start of FAIR. Later the collaboration aims at starting its in-beam program deploying the AGATA segmented \(\gamma\) array to study secondary-fragmentation, knock-out and relativistic Coulomb excitation reactions. For such campaigns AGATA will be followed by a magnetic transport system in order to help mass and charge identification of the outgoing ions in the LYCCA array.

The HISPEC-DESPEC collaboration is actively commissioning next generation implantation detectors, capable of sustaining higher implantation rates while presenting higher radiation hardness and faster responses. This will help the measurement of \(\beta\)-delayed neutron emission, where a low-threshold and fast response is required.

A dedicated campaign to measure nuclear moments, the g-SPEC campaign, is also under development with the design of a custom electromagnet and a linear version fo the DEGAS triple detectors.

In addition new analysis techniques and novel approaches to the analysis of the data are being developed in order to handle the increasing volume of acquired data and fully exploit the details of the digitally readout signals.

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