RECENT RESULTS FROM THE DESPEC CAMPAIGN AT GSI* **

G. Benzoni

on behalf of the HISPEC-DESPEC Collaboration

Istituto Nazionale di Fisica Nucleare, Sezione di Milano
Via Celoria 16, Milano, Italy

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The HISPEC-DESPEC Collaboration proposes to investigate the structure of nuclei produced by projectile fragmentation reactions, focusing on the investigation of heavy exotic nuclei, capitalising on the improved level of sensitivity offered by newly developed detectors coupled to the unique secondary beams available at the GSI-FAIR facility. In the early stages of the experimental activity at FAIR Phase-0, started in 2020, the collaboration focused the attention on the study of the internal structure of exotic systems using γ-ray spectroscopy following the internal decay of metastable nuclear isomeric states, and β-decays with lifetimes in the millisecond-to-second range. A description of the set-up and first results obtained in the experimental campaigns covering the years 2020–2022 are the subject of this paper.

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1. Introduction

The HISPEC-DESPEC (H/D) Collaboration, part of the NUSTAR research program, is planning to exploit the actual and future high- energy and intensity beams delivered by the GSI-FAIR accelerator complex, with two main objectives.

HISPEC (High-resolution In-flight SPECtroscopy) experimental programme aims at performing detailed spectroscopic studies by measuring outgoing γ radiation via nuclear and Coulomb excitation techniques. The core of the HISPEC setup is the Advanced GAmma Tracking Array (AGATA) [1], the latest generation array of segmented HPGe detectors, able to reconstruct the initial energy of the emitted γ radiation also in the case of large Doppler

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displacement caused by the relativistic energies at play. AGATA is coupled to ancillary detectors for specific measurements (*e.g.* plunger devices for level lifetimes determination, neutron detectors, *etc.*). The outgoing radioactive fragments are identified event-by-event by time-of-flight (TOF), energy loss, and total energy thanks to the LYCCA (Lund-York-Cologne Calorimeter) [2] in conjunction with a magnetic spectrometer.

In parallel, DESPEC (DEcay SPECtroscopy) experiments aim at a detailed study of the decay mechanism in the most exotic nuclear species at reach at GSI-FAIR, exploiting the measurement of decay half-lives, competing decay modes and isomeric states. 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 γ-detection array, DEGAS (DEspec Germanium Array Spectrometer), as well as the neutron array MONSTER (MOdular Neutron time of flight SpectromeTER) or the Beta-dELayEd Neutron detector (BELEN). In addition, the Decay Total Absorption Spectrometer (DTAS) and the FAst TIMing Array (FATIMA) can be employed.

The HISPEC-DESPEC Collaboration proposes decay spectroscopy (DESPEC) measurements as part of the Phase-0 GSI-FAIR experiments. The campaign, started in 2020, focused on the investigation of structural properties of exotic nuclei, with experiments spanning three regions of the nuclides chart: *(i)* heavy neutron-rich (n-rich) nuclei around and above ^{208}Pb, *(ii)* rare-earth nuclei, and *(iii)* proton-rich (p-rich) nuclei in the proximity of ^{100}Sn.

The region of heavy neutron-rich nuclei around and above ^{208}Pb is the key to understanding of the nucleosynthesis of heavy elements via the rapid neutron-capture (r) process. The persistence of the $N = 126$ and $Z = 82$ shell gaps, and the evolution of the underlying nuclear structure, are under investigation, with the scope of probing effective shell-model interactions and scrutinizing their predictions for the r-process. In addition, the DESPEC Collaboration aims at providing inputs to astrophysical nucleosynthesis models by measuring lifetimes and β-delayed neutron emission probabilities in heavy nuclei above ^{208}Pb, especially addressing the role of first-forbidden transitions.

Beside the quest in the heavy region of the nuclides chart, investigations of the nuclear properties of rare-earth nuclei are being performed. Here phenomena related to K-isomerism, large multipole excitations, and new deformed shell gaps are of high relevance.

In the region of the nuclide chart around ^{100}Sn, specific efforts have been directed towards assessing the robustness of the $N = 50$ and $Z = 50$ double shell closure, and the evolution of single-particle energies. In addition, being $N \sim Z$, the region is ideal to investigate the role of the proton–neutron pairing: protons and neutrons occupy identical orbitals close to the Fermi energy, therefore the Pauli principle is lifted and both isoscalar ($T = 0$) and isovector ($T = 1$) proton–neutron-pair correlations are allowed. Moreover, this is an ideal area to test the seniority symmetry, which describes the level scheme taking into account only the unpaired nucleons. The study of isomeric states and the radioactive decays can provide the first glimpses of the internal structure via its γ-ray 'fingerprints'. A systematic study of key experimental signatures, such as the energy of the first excited state and/or 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.

2. The DESPEC set-up for the GSI-FAIR Phase-0 campaigns

The exotic nuclei under investigation have been produced by the fragmentation reaction of the relativistic beams, provided by the LINAC+SIS18 accelerator complex of GSI-FAIR, impinged onto a primary target, located at the entrance of the FRagment Separator (FRS) [3]. 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. Position, time of flight (TOF), and energy loss in detectors located along the flying path in the intermediate focal planes of FRS, serve to reconstruct, on an event-by-event basis, the ions, using the $B\rho$–ΔE–$B\rho$ and TOF–$B\rho$–ΔE methods [4]. Passive slits and degraders help selecting the ions of interest and lowering the overall rate of detection.

The main identification is realised between the middle dispersive focal plane, S2, and the final focal plane, S4, with an S2 wedge degrader used in both achromatic and monochromatic modes. Additional X-slits at S2 and S3 help the selection of the desired nuclei and the reduction of the final rate on detectors. A pair of TPC (Time Projection Chamber) detectors are used to guarantee excellent position identification. In addition, time-of-flight (TOF) is measured using signals from plastic scintillator detectors located at S2 and S4. At the final focal plane, two MUSIC (MUlti Sampling Ionisation Chamber) detectors, with a stripper foil in between, provide the identification in terms of atomic charge.

During the Phase-0 campaign, several detector combinations have been exploited by the DESPEC Collaboration, revolving around the AIDA set-up, based on Double Sided Silicon Strip Detectors (DSSSD) characterised by a high degree of pixelation. Each unit is an 8×8 cm^2 DSSSD tile with a thickness of 1 mm, composed of 128×128 strips (16384 pixels), with a 0.560 mm inter-strip pitch. The DSSSDs are purchased as a single (8×8 cm^2) wafer or, triple (24×8 cm^2) wafer devices. The energetic (100–200 MeV/u) exotic heavy ions are implanted into a stack of DSSSDs to ensure a correct implantation depth for several species at the same time. The implanted nuclei undergo radioactive decay emitting low-energy β and α particles, protons, neutrons, and γ rays. The charged particles are then detected by the DSSSDs. Due to the high pixelation, one can define the position (X, Y, Z, depth) where the nucleus has been implanted to be correlated to the subsequent 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. AIDA runs as a triggerless system, and the EDAQ produces time-ordered data items with a 100 MHz 48-bit timestamp. To synchronise data from different data acquisition systems, AIDA uses the White Rabbit 1 GHz clock via a GSI-built VETAR2 module to the AIDA MACB clock distribution modules.

A combination of high-resolution, high-efficiency HPGe detectors and the FAst TIMing Array (FATIMA) set-up of $\mathrm{LaBr_3}$:Ce scintillators is used to measure the internal γ-deexcitation following internal deexcitation of the nuclei.

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 cm^2, demanded by the wider focal plane of the Super-FRS at FAIR, and well suited for the S4 focal plane of the FRS. The onboard 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. The MBS-based NUSTAR DAQ is employed for data acquisition [5].

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 36 $\mathrm{LaBr_3}$:Ce crystals with a diameter size of 1.5×2 inch^2 length. FATIMA can be used to determine lifetimes by measuring the time difference between two detected γ rays. Alternatively, it can be used to measure the lifetimes of excited states populated by β decay. In this case, the time difference between a γ ray and the β particle has to be measured. This can be achieved by sandwiching the implantation AIDA detectors between two fast plastic scintillators. If the β particle leaves the DSSSD and hits one of the plastic detectors, a fast signal is obtained. The fast plastic detector, named betaPlastic, consists of a tile of BC-400 scintillator material, readout by a series of SiPM glued to each side. Two betaPlastic detectors are used, one upstream and one downstream, sandwiching the DSSSD, each of them covering the same area as the AIDA detectors. The betaPlastic detector works 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 the described configuration, the total full energy peak efficiency of FATIMA at 1 MeV for the 36 detector array is 2.9%.

During the campaigns in 2020–2021, FATIMA was coupled to several HPGe detectors, either the Galileo Triple Clusters [6] (see top panel of Fig. 1), or the 7-fold Cluster detectors of the former EUROBALL array

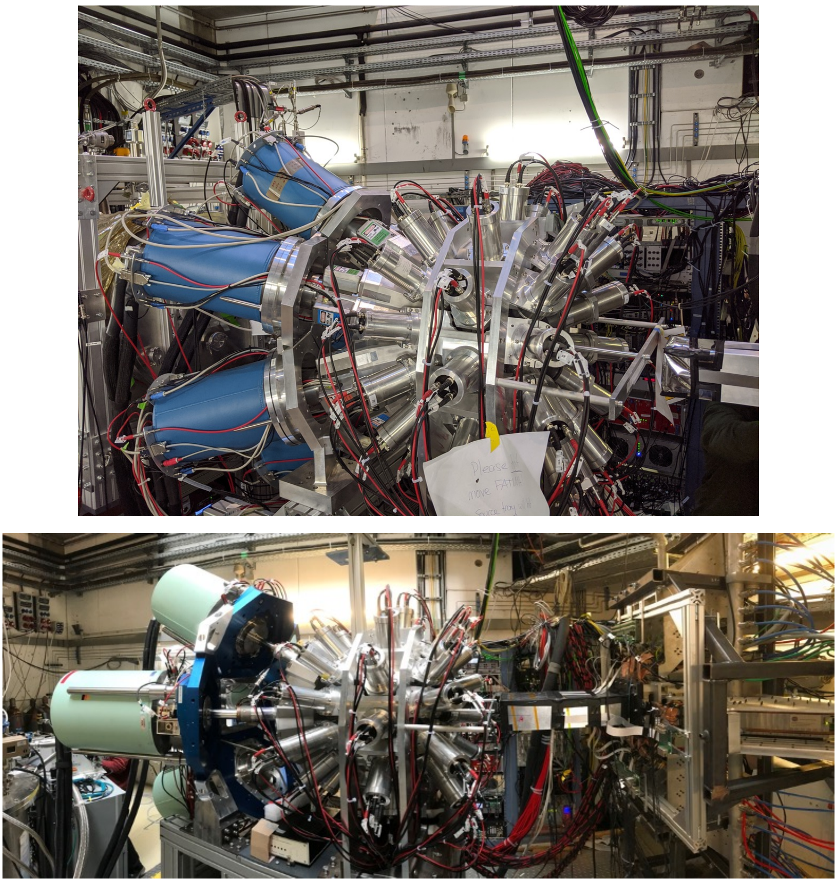

Fig. 1. (Colour on-line) Top panel: Experimental set-up used in the campaign in 2019–2020, where the coupling of the GTC (Galileo Triple Cluster) detectors (with blue dewars) and the FATIMA crystals (in the grey aluminium cases) are clearly visible. The narrow version of AIDA is used with this set-up. Bottom panel: Experimental set-up combining AIDA in its wide version (right side of the figure), FATIMA (centre of the picture in silver), and HPGe detectors (light blue on the left side), as used during the campaign in 2021.

(bottom panel). In this arrangement, the FATIMA set-up consists of 36 detectors arranged in 3 rings (3×12). AIDA and betaPlastic was used in both narrow and wide configurations (8×8 cm^2 and 24×8 cm^2), arranged either in 2 or 3 layers, depending on the experimental requirements. Details of the implementation of the FATIMA set-up at GSI are described in Ref. [7], while a further description of the DESPEC detectors implementation at GSI-FAIR is given in [8].

The increased γ-detection efficiency provided by the DEGAS array will allow to detect weak transitions and low-branching ratios from new and weakly populated states. In addition, the improved efficiency will help to reconstruct level schemes by allowing the analysis of high-fold coincidences and improved particle–γ correlations.

The high-resolution set-up here described can be replaced by the DESPEC Beta Decay Total Absorption Gamma-Ray Spectrometer (DTAS) [9–11]. 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 $15 \times 15 \times 25$ cm^3 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 ^{60}Co line. A picture of the installation is shown in Fig. 2.

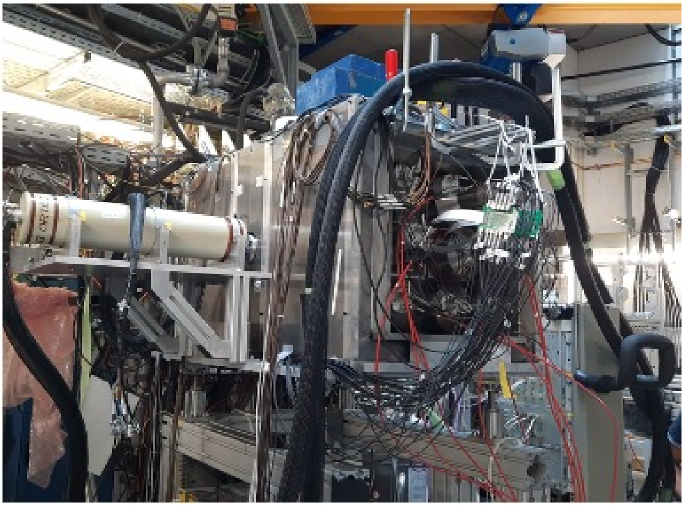

Fig. 2. DTAS installation at S4 area for the 2022 experimental campaign.

The experimental approach used in the campaign in 2020–2022 is well established, the DESPEC Collaboration having a long tradition in such studies. Novelties and the latest improvements are caused by 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. 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 almost all of its subsystem during the runs in 2020–2022, performing a series of experiments using AIDA, FATIMA, DEGAS, and DTAS, arranging them in various configurations. A picture of the set-up comprising HPGe detectors, FATIMA, and AIDA is shown in Fig. 1, while the DTAS installation is presented in Fig. 2, as they were arranged for the campaign in 2020 and 2021, respectively.

In 2020, the collaboration completed the S480 experiment (M. Górska, B. Cederwall, J. Jolie, and P.H. Regan), approaching the heaviest $N = Z$ nuclei by studying seniority and electromagnetic transition rates in ^{94}Pd, populated by fragmentation of a ^{124}Xe beam. Thanks to the Fast-Timing approach, allowed by the presence of $LaBr_3$:Ce detectors, the E2 strength for the $2^+ \to 0^+$, $4^+ \to 2^+$ transitions were measured in ^{94}Ru, exhibiting a drastic enhancement of transition strength in comparison with the pure-seniority model predictions as well as the standard shell-model predictions in the fpg proton hole space with respect to doubly-magic ^{100}Sn. This anomalous behaviour is ascribed to a subtle interference between the wave function of the lowest seniority, $\nu = 2$, $J^\pi = 4^+$ state, and that of a close-lying $\nu = 4$ state, that exhibits partial dynamic symmetry resulting in a quantum phase transition behaviour from the seniority conserved regime to a seniority mixed regime. Results of the successful measurement are published in [12]. Further details are found in [13].

The FATIMA set-up was also employed during the campaign in 2021, where three experiments were performed: S452 (V. Werner, J. Jolie, N. Pietralla, P.H. Regan), S460 (G. Benzoni, J.J. Valiente-Dobón), and S496 (G. Zhang and D. Mengoni). In the last run, the new layout of AIDA covering the full focal plane with 3 DSSSD tiles was employed. During the campaign in 2021, three different regions in the nuclide chart were covered:

the first experiment focused on shape evolution in the $A \sim 190$ region, in particular, focusing on n-rich W isotopes. The second experiment performed a study of octupole deformation in the region of mass around $A \sim 225$, where little to no experimental information on the internal structure and decay half-lives is available. Further details are found in [14]. The last experiment of the 2021 campaign focused on the ^{100}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.

For the campaign in 2022, the first realisation of the DEGAS array was coupled to the wide version of AIDA for the S450 experiment (Zs. Podolyak), while later in the year, the DTAS array was successfully used for the S505 run (A.I. Morales, E. Nacher, and J.L. Tain). The two experiments aimed at attacking the same region in the chart of nuclides, around $N = 126$, accessing the isomeric and β-delayed γ 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(GT) response thanks to the total absorption spectroscopy made available by the DTAS scintillators.

4. Future perspectives

After a short campaign at RIKEN (Japan), the FATIMA array will be back to GSI-FAIR in 2024, to be used together with the DEGAS and AIDA detectors, for additional campaigns within the FAIR Phase-0 framework. Beams from SIS18 will further increase in intensity and allow to continue to 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 excellent work of the GSI accelerator department, the fruitful discussions and collaborative efforts of the FRS team, the ingenuous solutions of the mechanics and electronic workshops in GSI are here acknowledged. This work is carried out as part of FAIR Phase-0 at the GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany.

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