

## PRESENT AND FUTURE OF HISPEC\*

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The HISPEC (High-resolution in-flight SPECTroscopy) project is part of the core experimental facility at FAIR. It is aimed at nuclear structure and reaction studies, using high-resolution  $\gamma$ -ray spectroscopy as its main tool. Experiments using the same techniques were performed at the forerunner RISING project at the existing GSI. Some HISPEC detectors are already in the production phase, with the first commissioning experiments taking place in 2010. The physics case, the experimental setup, the opportunities opened are discussed.

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### 1. Introduction

Nuclear physics is being revolutionised by the appearance of new radioactive ion beam (RIB) accelerator facilities. Among these, the FAIR (Facility for Antiproton and Ion Research) complex [1] is being built in Darmstadt, Germany at the site of the present GSI. FAIR will provide unique opportunities in the fields of hadron, nuclear, atomic, and laser physics, and applications and is recognised by ESFRI (European Strategy Forum on Research Infrastructures) as the major RIB in-flight facility for Europe. It will provide capabilities unmatched worldwide. FAIR will be able to produce intense, high brilliance beams of all stable chemical elements up to uranium with energies in the range  $E/A \sim 1\text{--}30$  GeV and also antiprotons. Beams of short-lived radioactive species will be generated in fragmentation/spallation and fission reactions. Such an in-flight facility has the advantage of being able to provide any isotope independent of the chemical properties of the element and, since the production process is fast, it can produce beams of the shortest-lived, and hence most exotic, nuclei. FAIR will be unique among

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the planned fragmentation facilities in several ways: *(i)* it will provide the cleanest radioactive beams for heavy nuclei; *(ii)* experiments can be carried out at high energies up to 2 GeV per nucleon; and *(iii)* it is planned to have storage rings.

The HISPEC (High-resolution In-flight SPECtroscopy) project [2] will use the high-intensity radioactive beams delivered by the Superconducting Fragment Separator [3]. There will be an increase of the beam intensity of orders of magnitudes when compared to GSI, based on two main factors: *(i)* higher primary beam intensity delivered by the accelerator complex, and *(ii)* higher transmission through the fragment separator, especially for fission products.

## 2. Physics questions and tools of HISPEC

The physics case of HISPEC is part of the overall NuSTAR (Nuclear Structure, Astrophysics and Reactions) [4] physics programme. NuSTAR is an “umbrella” collaboration of more than 800 scientists from 146 institutions in 36 countries (Nov. 2007). It comprises nine different collaborations (AIC, DESPEC, ELISe, EXL, HISPEC, ILIMA, LaSpec, MATS and R3B) based around state-of-the art detector systems. The common aim of NuSTAR is to exploit the beams of short-lived radioactive species to study how the properties of nuclei and nuclear matter vary over a wide range of isospin, angular momentum, temperature and density. NuSTAR will provide data on nuclear many-body systems under extreme conditions. The ultimate goal is to find a unified description of the properties of nuclei and nuclear matter. NuSTAR will enable the nuclear physics community to address many of the key questions in nuclear structure, reactions and astrophysics. In particular, it will facilitate experiments to address the following fundamental questions [4]:

- What are the limits of nuclear existence? What is the heaviest element we can make and where does the neutron-dripline lie?
- How does the ordering of quantum states, with all of its consequent implications for nuclear structure and reactions, alter in highly dilute or neutron-rich matter?
- Do new forms of collective motion occur far from the valley of nuclear stability?
- Are there new forms of nuclear matter in very loosely bound nuclear systems?
- Do symmetries seen in near-stable nuclei also appear far from stability and do we observe new symmetries?
- How are the elements and isotopes found in the Universe formed?

HISPEC is a versatile, high-resolution, high-efficiency spectroscopy set-up to address the above listed key nuclear physics questions using radioactive beams with energies of  $E/A = 3\text{--}200$  MeV. HISPEC will concentrate on those aspects of the physics investigations which can be best addressed with the proposed high-resolution setup using the unique beams of FAIR. A schematic drawing of the HISPEC experimental setup is shown in Fig. 1 [5].

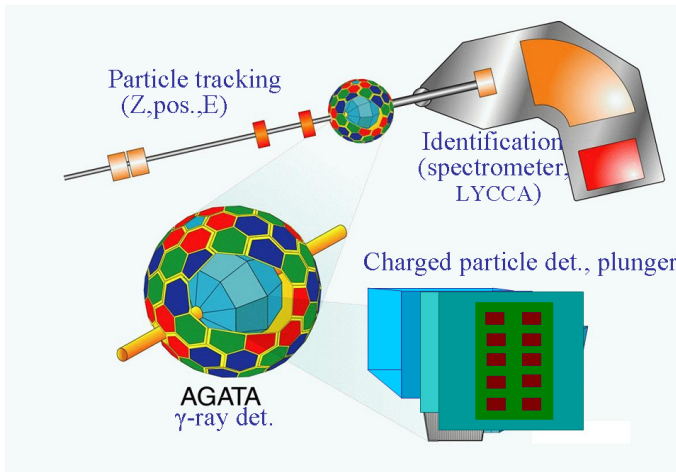


Fig. 1. Schematic view of the HISPEC experimental setup.

Within HISPEC two different beam-energy regimes will be used, with the focus on intermediate beam energy ( $E/A \sim 100$  MeV) experiments. Table I lists the corresponding techniques and required beam intensities [2].

TABLE I

Experimental opportunities for high-resolution in-flight spectroscopy (HISPEC) at FAIR.

| Experimental method<br>(beam-energy range)                                                                        | Beam intensity<br>(particle/s) |
|-------------------------------------------------------------------------------------------------------------------|--------------------------------|
| Intermediate energy Coulomb excitation,<br>secondary fragmentation<br>( $E/A \sim 100$ MeV)                       | $10^1\text{--}10^5$            |
| Multiple Coulomb excitation,<br>direct and deep-inelastic,<br>fusion-evaporation reactions<br>( $E/A \sim 5$ MeV) | $10^4\text{--}10^7$            |

Detailed spectroscopic information will be deduced by  $\gamma$ -ray, charged-particle and neutron spectroscopy in reactions of secondary beams at intermediate energies. Thick targets, of the order of several 100 mg/cm<sup>2</sup> can be used, and relevant cross-sections are of the order of 0.1 barn. Single step Coulomb excitation and fragmentation reactions at intermediate energies will be employed.

Thinner targets will be used at Coulomb barrier energies. Multiple Coulomb excitation have the highest cross-sections, but direct and fusion-evaporation reactions might be also possible.

### 3. The HISPEC detectors: description and status

HISPEC aims at complete spectroscopy of all the particles and gamma rays which are emitted, as well as event-by-event identification of the nucleus of interest.

The following detector systems will be used for the HISPEC experiments:

- detectors for beam tracking and particle identification,
- the AGATA tracking Ge array, as well as other  $\gamma$ -ray detectors,
- devices for precision lifetime measurements (plungers, BaF<sub>2</sub>/LaBr<sub>3</sub>(Ce) arrays),
- charged-particle Si detector arrays optimised for reaction and structure studies,
- large acceptance magnetic spectrometer with “tagging” detectors in the focal plane.

We note that HISPEC shares several components with the DESPEC (decay spectroscopy) [6] project. Research and development, prototyping and tests of these detector systems are carried out by different sub collaborations in charge of building the various detectors.

#### 3.1. AGATA

The Advanced GAMMA Tracking Array (AGATA) [7] will be at the heart of HISPEC. In its final configuration it will cover the full  $4\pi$  and will consist of 180 germanium crystals, with one cryostat for every three crystals. Each detector crystal is segmented  $6 \times 6 = 36$  ways. In addition to segmentation, pulse shape analysis is used to determine the interaction position of the gamma rays with an accuracy of  $\sim 2$  mm. Tracking algorithms are employed to reconstruct the path of the gamma-rays. Tracking arrays will result in unprecedented sensitivity, by improving both the photo-peak efficiency and the peak-to-total ratio. The effect of the ancillary detectors have been simulated, with special emphasis to the effect of uncertainties in

energy, position and angle of the  $\gamma$ -ray emitting particles. The requirements on beam tracking detectors have been determined [8,9] and concluded that this performance can be achieved with existing technologies. The AGATA demonstrator, consisting of 15 Ge crystals in 5 cryostats is being tested at Legnaro National Laboratories, Italy. A physics campaign will start at the beginning of 2010. It is envisaged that the AGATA demonstrator will be moved to GSI and used at the SIS-FRS facility from the end of 2011. More details are given in Section 5.

### 3.2. HYDE

The HYbrid DETector (HYDE) array is being developed for the detection of charge particles and will be used for reaction studies. Simulations, tests of detectors and electronics have been performed, and a prototype detector is being built [10]. Detailed information about the status and future of HYDE can be found in Ref. [11].

### 3.3. Plunger

Differential plunger devices will be employed to measure the lifetime of excited states. In this devices the usual stopper foil is replaced by a degrader foil to enable the detection of the nuclei of interest downstream, needed in order to clean the spectra of strong background radiation. Differential plunger devices specifically designed for fragmentation beam experiments use large area target and degrader foils. Such devices were built by the Köln group and used in experiments at MSU. Lifetimes were deduced following the excitation of nuclei both in secondary fragmentation [12] and Coulomb excitation [13] reactions. The gained experience will be used at HISPEC. It is expected that the first commissioning run at GSI will be in 2010, with experiments starting in 2011.

### 3.4. LYCCA

The Lund–York–Cologne Calorimeter (LYCCA) [14] is aimed to the identification of the reaction products. It is based on TOF- $dE$ - $E$  measurements. The atomic number will be determined from the energy loss in double-sided Si-strip detectors (DSSSD). The DSSDs will provide position information as well. The mass will be determined from the total energy and velocity (time of flight) measurements. Total energy is measured by CsI detectors. The measurement of the time-of-flight between the target position and LYCCA is ultimately to be performed with polycrystalline diamond wafers. During the physics driven commissioning phase at the existing GSI fragment separator and an early implementation phase, the stop signal of the time-of-flight measurement will be backed up by a system comprising a large-area ultra-fast scintillator in conjunction with multiple photomultiplier tube readout.

LYCCA goes beyond the previously employed system CATE [15]. CATE was based on  $dE$ - $E$  measurement only, therefore it was unable to give unambiguous mass identification.

LYCCA is being built as a flexible array of detector modules, allowing different configurations. The LYCCA Technical Design Report was accepted by FAIR. The simulated performance is published in Ref. [16]. Unambiguous identification is expected to be achieved up to mass  $A \sim 100$ . All the elements, both detectors and electronics, as well as the mechanical structure are ready. The prototype diamond detectors as well as the large area ultra-fast scintillation detector with multiple photomultiplier tubes were tested with GSI beams in October 2009. The first configuration of the detector system, LYCCA-0 will be commissioned and employed in physics driven experiments starting from 2010.

### 3.5. Magnetic spectrometer

The study of the heavy nuclei is a key part of the physics case, as FAIR will be unique in providing heavy fragments. In order to identify heavy ( $A > 100$ ) reaction products magnetic rigidity measurements have to be combined with the TOF- $dE$ - $E$  provided by LYCCA. It is envisaged that the first part of the energy buncher [17,18] will serve as high-resolution magnetic spectrometer. A possible design of the magnetic spectrometer/buncher is shown in Fig. 2. Due to its large size, the buncher/magnetic spectrometer cannot be hosted in existing FRS caves, and it can be used only after the so called low-energy cave at FAIR/NuSTAR becomes functional.

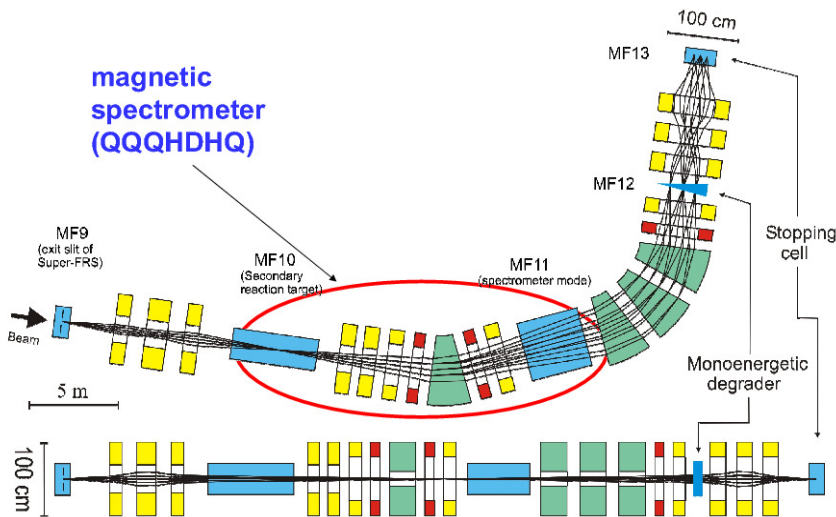


Fig. 2. A possible design of the magnetic spectrometer [19] of HISPEC.

### 3.6. Beam detectors

The beam identification and tracking detectors [20] have to provide, on an event-by-event basis, mass, charge, energy, position and direction information of the ions impinging on the secondary target. In the case of the intermediate energy experiments ( $E/A \sim 100$  MeV) the standard SuperFRS detectors will be used for this purpose. However, for experiments using radioactive beams slowed down to Coulomb barrier energies, special detectors have to be developed. In order to avoid excessive energy and angular spread very thin detectors have to be used. The developments concentrated on secondary electron emitting carbon foil detectors. In addition of being the thinnest detectors, they are fast and have good position resolution. Such detectors, similar to one used at the VAMOS focal plane [21] are built in Köln and Sevilla. Tests with diamond detectors have been also performed [22]. In addition, several tests with different detectors were performed using GSI beams with the ultimate aim to devise a physics driven proof of principle experiments [23]. We note, similar experiments with slowed down fragmentation beams run at RIKEN [24].

## 4. Past and present of HISPEC: RISING

The RISING (Rare ISotopes INvestigation at GSI) [25] is the precursor [26] project of both HISPEC [2] and DESPEC [6]. The  $\gamma$ -ray detection was based on 15 Euroball cluster Ge detectors. The fast beam experiments [27] were performed in the period 2003–2005 with the Ge-array positioned at forward angles (see Fig. 3). The photo-peak efficiency measured at 1.3 MeV was 1.3%, which corresponds to 2.8% for nuclei moving with a velocity of  $\beta = v/c = 0.43$  ( $E/A = 100$  MeV) [27]. To enhance the  $\gamma$ -ray detection capabilities of the system, in some experiments MINIBALL Ge detectors [28] were added at 90 degrees and large volume BaF<sub>2</sub> detectors at backward angles.

The energy of the secondary beams was in the  $E/A = 100$ –600 MeV range, with beam intensities (for a single isotope) in the order of  $10^2$ – $10^4$  ion/s. Both Coulomb excitation and secondary fragmentation experiments were performed. For example, Coulomb excitation of  $^{54,56,58}\text{Cr}$  nuclei [29] provided information about the shell evolution around  $N = 34$ . Secondary fragmentation reactions were used to test isospin symmetry at the drip line, by measuring the energy of the  $2^+$  state in  $^{36}_{20}\text{Ca}_{16}$  [30]. In addition, the possible use of the distinct lineshapes for lifetime determination was demonstrated [31] in the case of secondary fragmentation reactions.

Experiments performed with relativistic energy beams are characterised by a large background of atomic origin produced whenever fast ions pass through matter. Simulations [32] as well as the acquired expertise [27] will help in reducing this unwanted background in the future.

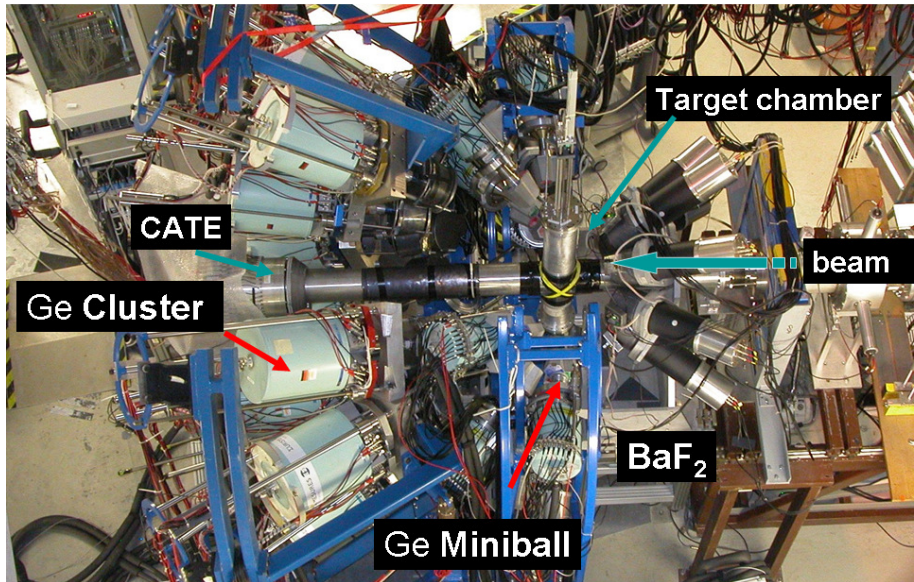


Fig. 3. Photograph of the RISING fast-beam array.

### 5. Future of HISPEC: PRESPEC and FAIR

PRESPEC is aimed at preparing for the spectroscopy to be carried out with HISPEC and DESPEC at FAIR by commissioning and employing components developed for HISPEC/DESPEC already at the existing GSI facility SIS-FRS. HISPEC type experiments will start in 2010. Compared to the RISING campaign several improvements will be made. The identification of the reaction products will be done with the LYCCA array. Unambiguous mass and  $Z$  identification will be possible up to mass  $A \sim 100$ . Experiments with a purposely build Köln differential plunger as well as measurements with the Saclay liquid hydrogen target are also planned. It is envisaged that the AGATA demonstrator will be moved to GSI in 2011, with experiments planned for the period 2011–2013. It is hoped that at that time about 8–10 triple clusters will be available. Simulations show that the use of this array will increase the  $\gamma$ -ray detection sensitivity by an order of magnitude when compared to the previous RISING [27] setup; an increase of a factor of  $\sim 3$  in photo-peak efficiency, as well as a similar improvement in energy resolution is expected [33].

It is envisaged that in some experiments MINIBALL Ge detectors [28] as well as large volume  $\text{LaBr}_3(\text{Ce})$  detectors will be coupled to the AGATA demonstrator in the coming years. On a longer time scale, in some experiments the PARIS detector array [34] might be used for  $\gamma$ -ray detection.



This high efficiency  $4\pi$  array will have a relatively good energy resolution, achieved by using  $\text{LaBr}_3(\text{Ce})$  scintillation detectors. The use of the PARIS array might be advantageous in experiments not requiring the energy resolution of Ge detectors, such as giant dipole resonance measurements [35].

During the RISING experiments the rate limitations came from the scintillation detector in the intermediate focal plane of the fragment separator and by the ionisation detector at the final focal plane. Both rate limits will be increased significantly by using segmented scintillation detectors and by digital processing of the ionisation chamber signals, respectively. Improvements are also made on the data acquisition in order to cope with higher event rates [36].

The experiments within the PRESPEC campaign will profit from the increased beam intensities achieved in the recent years. The improvements are based on the use of faster ramping of the SIS magnets (now 4 T/s), better transmission between the LINAC and SIS accelerators, rebuilding of the MEVVA source.

After the completion of the Super Fragment Separator [3] the HISPEC setup will be moved into the new cave of the low-energy branch [26]. A sketch of the layout is shown in Fig. 4. Here HISPEC will profit of the higher secondary beam intensities provided by the separator. The beam improvements will be based on the higher primary beam intensities of the new accelerator complex and on the higher transmission as well as selectivity (cleaner beams) of the SuperFRS. The reaction products will be identified by combining the

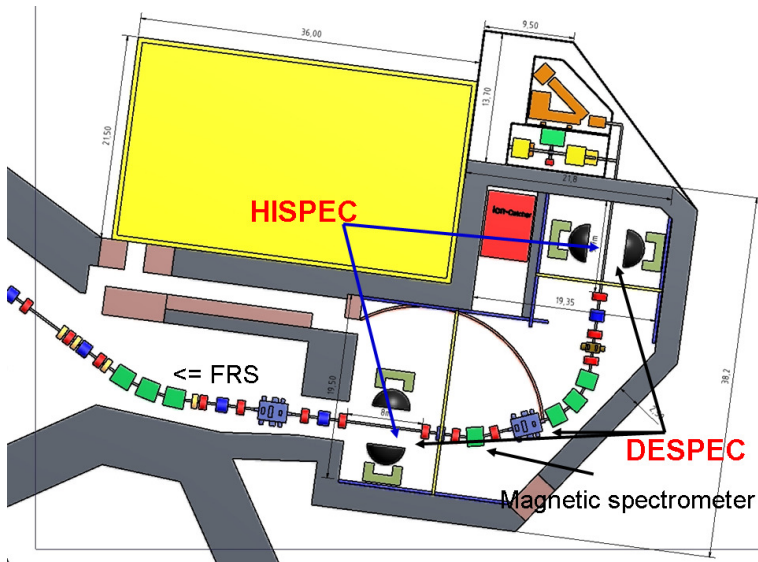


Fig. 4. Schematic view of the low-energy cave of FAIR.

LYCCA array with a magnetic spectrometer, therefore unambiguous mass and  $Z$  identification will be achieved even for the heaviest fragmentation products. With all the HISPEC detectors on line, the efficiency and selectivity of the detection system will be greatly improved. The majority of the experiments will be performed with HISPEC positioned before the magnetic spectrometer, although positioning after the energy buncher for cases when monoenergetic beams are required will be also possible (see Fig. 4.). Recoil decay tagging experiments with the decay detectors (of the DESPEC project) positioned after the magnetic spectrometer will become feasible.

## 6. Conclusions

HISPEC is a core project of the FAIR facility. Its tools, that of the high-resolution in-flight spectroscopy were used in the previous physics campaigns of RISING at GSI, under similar conditions. The HISPEC setup is designed and the first detectors will be already commissioned starting from 2010. With the improved beam intensity and beam quality of FAIR, combined with the state of the art equipment of HISPEC, high-resolution in-beam spectroscopy will remain a powerful tool in addressing key nuclear physics questions.

HISPEC is a large international collaboration. The contributions made by all participants [5] is acknowledged.

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