From RISING to HISPEC/DESPEC

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Abstract

The Rare ISotopes INvestigations at GSI (RISING) project is aimed at nuclear structure and reaction studies using high-resolution gamma-ray spectroscopy as its main tool. At the future FAIR facility, these tools will be employed by the High-resolution In-flight SPECtroscopy (HISPEC) and DECay SPECtroscopy (DESPEC) projects. The improvements in the experimental setups, together with the opportunities to be opened, are discussed.

Key words: spectroscopy, fragmentation, nuclear structure
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1. Introduction

The next generation European fragmentation-based radioactive beam facility is part of the Facility for Antiproton and Ion Research (FAIR) project[1]. The new facility will provide beams of radioactive ions with unprecedented intensities with the aim of studying the atomic nucleus. The HISPEC (High-resolution In-flight SPECtroscopy) and DESPEC (DEcay SPECtroscopy) projects address nuclear physics questions using radioactive beams at energies of E/A<200 MeV. The projects focus on those aspects of nuclear investigations with rare isotope beams which require high-resolution γ-spectroscopy setups.

At present, the GSI facility provides radioactive ion beams produced in fragmentation and in-flight fission. The RISING (Rare ISotopes INvestigations at GSI) project exploits these beams, with experiments performed at two energy regimes so far, E/A=0 (at rest) and E/A≈100 MeV.

The planned technical improvements as we move from RISING to HISPEC/DESPEC are discussed in the present paper. The resulting much increased efficiency will allow for both the study of nuclei further away form the stability and the application of new techniques. The schematic layout of the FAIR facility, including the existing GSI, with the location of the projects discussed, is shown in figure 1.

2. From GSI to FAIR

The Facility for Antiproton and Ion Research[1,2] (FAIR) will be built in an international collaboration at the site of the present GSI laboratory in Darmstadt, Germany. The primary beam will be accelerated by the existing linear accelerator (UNILAC) and synchrotron (SIS), and the new synchrotron (SIS100/300). The primary beam intensity will be increased by about a factor of ≈100 compared to the existing GSI facility. This increase is due to two main factors (i) a higher number of nuclei circulating in the ring, achieved by having ions in a lower charge state thus overcoming the present limitations due to the space-charge limit, and (ii) shorter acceleration times, achieved by using fast ramping magnets in the synchrotrons. The FAIR facility will be able to produce intense, high brilliance primary beams of all stable chemical elements up to uranium with energies in the range E/A 1-30 GeV and also anti-protons. Beams of short-lived radioactive species will be generated in fragmentation/spallation and fission reactions. The Super FRagment Separator (SuperFRS) [3] will be used to identify and separate the species of interest. The SuperFRS, compared to the existing Fragment Separator [4] will provide (i) 'cleaner' beams (due to its six dipole magnets as opposed to four) and (ii) higher transmission (due to the higher apertures of its magnets), especially for fission products.

Such a fragmentation facility is complementary to the Isotope-Separation-On-Line facilities, such as ISOLDE and SPIRAL2. It has the advantages of being able to provide any isotope independently of the chemical properties of the element and the process is fast, resulting in beams of the shortest-lived, and hence most exotic nuclei (albeit at lower optical quality than those at ISOL facilities). FAIR will be unique among the fragmentation facilities in several ways:

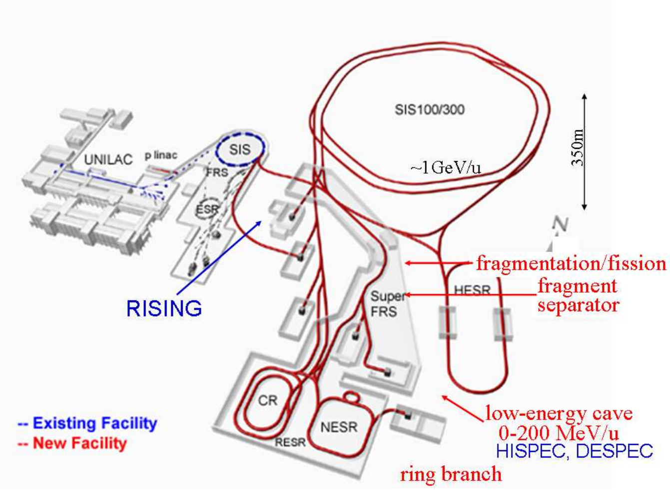

Fig. 1. Schematic view of the FAIR facility. The location of RISING at the present GSI facility, and the location of HISPEC and DESPEC at the future FAIR facility are indicated.

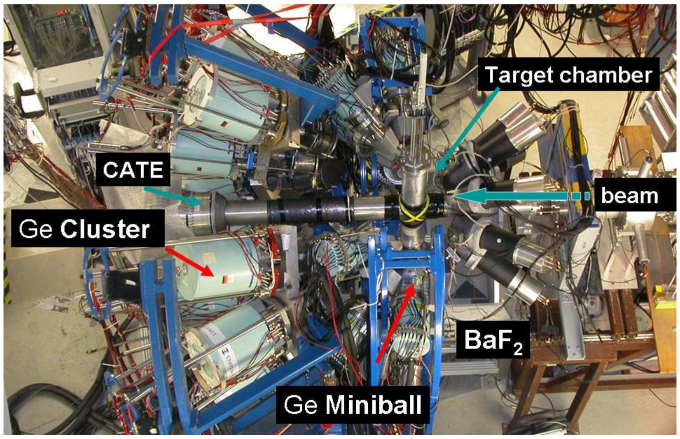

Fig. 2. Photograph of the RISING array in its configuration used for fast beam experiments.

(i) experiments can be carried out at high energies up to E/A≈2 GeV, (ii) cleanest radioactive beams for heavy nuclei, (iii) the existence of storage rings (see figure 1).

Both HISPEC and DESPEC will be located on the low energy branch of the SuperFRS, and they will profit from the unique beam properties, such as: (i) several thousands of isotopes of all elements between uranium and hydrogen can be uniquely prepared as beams with energies from about E/A=0 (stopped beam) MeV to E/A=200 MeV and with intensities appropriate for in-flight spectroscopy, (ii) ions with very short lifetimes (a few 100 ns) can be studied, (iii) beams composed of several isotopes, mono-isotopic beams and beams in high spin isomeric states will be available, (iv) the beam quality enables high resolution γ-spectroscopy, including angular correlations, polarisation, g-factor and lifetime measurements, (v) for energies around the Coulomb barrier employing the New Experimental Storage Ring even high resolution particle spectroscopy becomes possible.

The physics case for the HISPEC/DESPEC experiments [5,6] is part of the overall NUSTAR physics programme[7] and shares the common goals of attempting to understand nuclear structure and nuclear reactions and related questions in nuclear astrophysics. The collaboration will concentrate on those aspects of nuclear structure, reactions and astrophysics investigations which can be exclusively addressed with the proposed high resolution spectroscopy set-up using the beams unique to the FAIR facility. The technical proposal of HISPEC/DESPEC can be found at ref. [8].

3. From RISING to HISPEC

Within the HISPEC project the nuclei of interest will be populated in-flight, using nuclear and Coulomb excitation reactions. Detailed spectroscopic information will be deduced by γ-ray, charged-particle and neutron spectroscopy. The experimental techniques to be used can be grouped together in relation to two different energy regimes. Secondary fragmentation and single step Coulomb excitation will be used at intermediate, E/A≈100 MeV, energies. Thick targets, of the order of several 100 mg/cm^2, can be used and relevant cross sections are of the order of 0.1 barn. Such experiments have been already performed at RISING [9] (see figure 2). For example: Coulomb excitation of ^{54,56,58}Cr nuclei [10], providing $B(E2; 2^+ \rightarrow 0^+)$ transition strenghts, gave information about the shell evolution around N=34; secondary fragmentation reactions were used to test isospin symmetry at the drip line, by measuring the 2^+ excited state in ^{36}Ca [11].

At Coulomb barrier energies thinner targets will be used, and consequently higher beam intensities will re required. Such experiments have not been performed at RISING yet. The main difficulties arise from the need of tracking of such low-energy beam particles. Tests were already performed, and more planned, with the aim to gain experience on tracking low-energy, high-emittance beams [12].

The schematic view of the HISPEC setup is shown in figure 3. HISPEC will comprise beam tracking and identification detectors placed before [13] and behind the secondary target, the AGATA Ge array, charged particle detectors, plungers, a magnetic spectrometer and other ancillary detectors.

3.1. *The AGATA spectrometer*

The HISPEC set-up has at its core AGATA [14], the next generation gamma-ray tracking array, with a resolving power hugely exceeding the presently available Ge-arrays. AGATA (Advanced Gamma Tracking Array) is designed to be a 4π detector consisting of 180 germanium detectors. Each detector crystal will be segmented 36 ways. Within each detector pulse shape analysis will be used to deter-

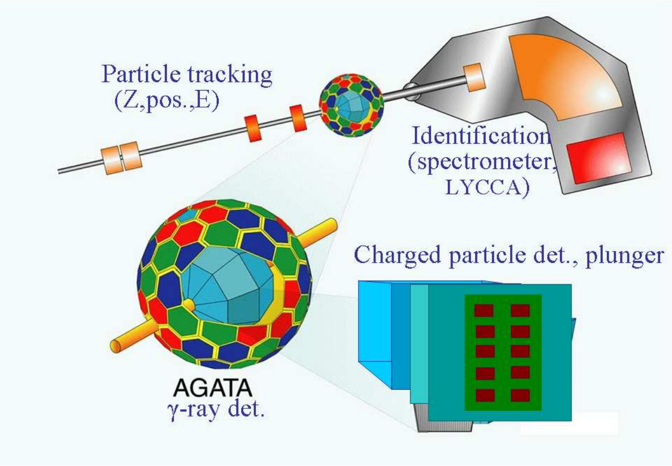

Fig. 3. Schematic illustration of the HISPEC experimental setup.

mine the interaction positions of the gamma rays to an accuracy of 2 mm. Tracking algorithms will be employed to reconstruct the paths of gamma rays passing through the detectors.

The effect of ancillary detectors (charged particle arrays, plunger) to be used in conjunction with AGATA has been simulated. Special emphasis was given to the uncertainties in energy, position and angle of the γ-ray emitting particles. The requirements with respect to the beam tracking detectors have been determined [15,5], and this performance can, in principle, be reached with existing technologies.

The AGATA demonstrator, consisting of five triple cluster modules (15 Ge crystals) will start to operate in Legnaro National Laboratories, Italy, in 2008. It is envisaged that AGATA will be moved to the SIS-FRS facility in around 2011 for an early implementation physics programme within the HISPEC project. It is expected that 45 detectors, covering a solid angle of 1π will be available at that time. They will be placed at a distance of $\approx$15 cm at forward angles. The calculations predict a photopeak efficiency for this 1π array of $\approx$15% for E/A=100 MeV (β=0.43), and an energy resolution better than 1%. In contrast, the full peak efficiency of the 15 cluster detectors of the RISING array in its fast beam configuration [9] is 2.8% for a 1.3 MeV gamma ray emmitted in-flight at E/A=100 MeV.

The energy resolution is ΔE/E<2%. This represents an increase of a factor of $\approx$6 in efficiency compared with RISING in singles and even higher for coincidence spectroscopy. It will enable highly selective $\gamma\gamma$-coincidences to be measured in fragmentation reactions. The collaboration will investigate if the 15 Cluster detectors should also be used for specific experiments. These could be located at backward angles to increase the efficiency, or mounted in a stand alone frame downstream of the target.

3.2. *Identification after the secondary target*

For the identification of isotopes following different types of reactions in the secondary target, versatile charged-particle detector arrays with different geometries must be constructed, including the potential of coupling them with a magnetic spectrometer. The LYCCA array will consist of dE-E telescopes and in addition it will measure the time-of-flight between the reaction target and the array. For TOF measurement three options are considered and these are being tested, using: polycrystalline diamond, ultra fast scintillators and Si detectors with fast electronics. According to simulations, this system will allow the identification of ions up to a mass of A$\approx$100. In contrast, the present CATE array [16] is based on dE-E measurements only. It allows for element determination through the dE measurement. However, the mass of the ions cannot be uniquely determined due to the uncertainties in the velocity of the ions. These uncertainties arose from energy straggling in the target and from the reaction mechanism itself. The TOF measurement of LYCCA will overcome this problem.

For heavier ions (A>100) an additional momentum dispersion Δp/p provided by a magnetic device is necessary to achieve the desired mass resolution. The ionic charge state distribution has also to be determined. The ultimate solution is the combination of an ion-optic device providing A/q separation and possibly magnetic focusing in combination with the LYCCA array comprising tracking- and ΔE/E detectors. The first part of the energy buncher [17,18] will serve as high-resolution magnetic spectrometer.

3.3. *Other HISPEC detectors*

Several other detectors will be available to be used in conjunction with AGATA. Plunger devices can be used for lifetime measurements. The usual stopper foil will be replaced by degrader foils to enable the detection of the nuclei of interest downstream of the degrader foils in order to clean the spectra of the strong background radiation. Other possible detectors include novel scintillator detectors, such as $LaCl_3$(Ce) and $LaBr_3$(Ce) for gamma-ray detection, as well as Si detectors from prompt charged particle emission. For nuclear reaction studies at relatively low energies (E/A=10-50 MeV) the 4π HYbrid DEtector array (HYDE) [19] is being developed for the detection of charged particles.

4. From RISING to DESPEC

The radioactive ion beams can be stopped and their consequent decay measured. These radioactive decays (α, β, γ, proton and neutron) will be measured and position-correlated with implants. Key physics information such as particle decay branching ratios, half-lives, first excited states and isomeric decays will be obtained. The technique is very sensitive, the needed beam intensities are in the order of 10^{-5}–10^{3} ion/s.

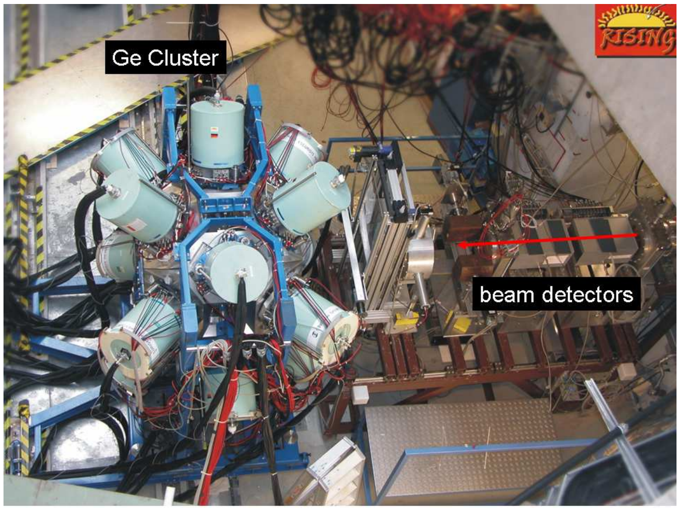

Fig. 4. Photograph of the RISING array in its configuration used for stopped beam experiments.

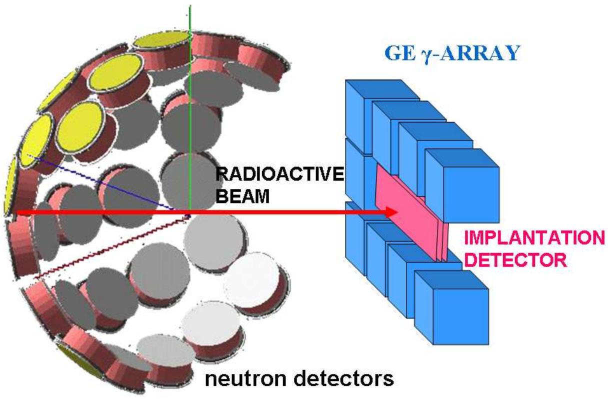

Fig. 5. Schematic illustration of the DESPEC experimental setup.

Decay measurements have been performed with the present RISING, with the detectors surrounding the target in spherical symmetry (see figure 4.). Both isomeric decay experiments using passive stoppers (including magnetic moment measurements [20]), and beta-decay experiments using active Si stopper have been performed. The photopeak efficiency of the RISING array in its stopped beam configuration [21] is 10% at 1.3 MeV. Highlights include the study of the structure of the r-process pass nucleus ^{130}Cd by internal isomeric decay [22] and conversion electron spectroscopy in the N=126 ^{205}Au nucleus [23].

The DESPEC setup [6] will comprise a Si based implantation and decay detector, a compact Ge array, neutron detectors, total absorption spectrometer, scintillation detectors (BaF_2, $LaCl_3$(Ce), $LaBr_3$(Ce)) and equipment for moment measurements of long-lived states. A schematic view of DESPEC setup is shown in figure 5.

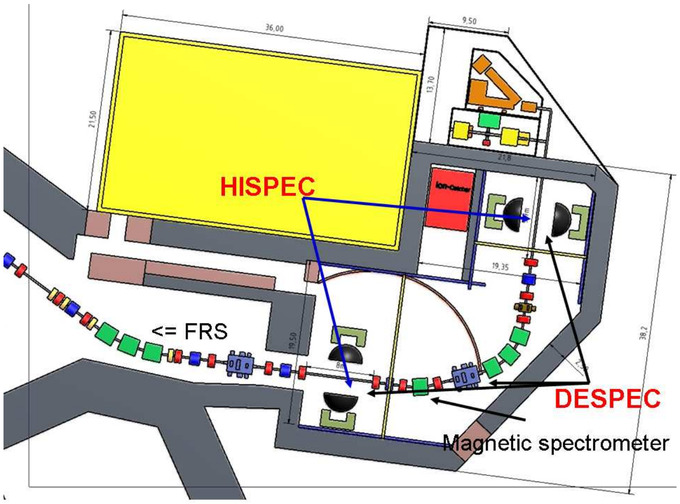

Fig. 6. Schematic view showing the possible positions of the HISPEC and DESPEC experimental setups in the low energy cave.

The implantation and decay detector based on Si DSSD technology will measure both the very high energies (GeV) deposited by the radioactive ions as they stop in the DSSD stack, and the subsequent decay events with MeV energies for protons and alpha particles and an energy loss (dE) of a few hundred keV in the case of β particles. This represents an extremely large dynamic range and demands a very low energy threshold, of the order of a few tens of keV. The low treshold is particulary important in the case of internal decay studies, through converion electron detection. The detector system will consist up to a maximum of eight 1 mm layers of Si, covering an area of 8 cm x 24 cm. Each detector of size 8 cm x 8 cm will have 128 vertical and 128 horizontal strips. The high segmentation of the DSSDs minimises the effects of random correlations between successive implants and decays, and between implants and the decay of long-lived activities.

High-resolution γ-ray detectors will be positioned around the implantation detector. A highly flexible and modular γ-ray detection array consisting of 24 stacks of planar pixelated (or double-sided strip) Ge detectors is proposed [24]. These modules can be arranged in different geometries optimised to the different types of experiments envisaged at DESPEC. The high granularity of the Ge detectors is important in order to assure high efficiency of the array during the "prompt flash" of radiation associated with the implantation of high energy ions into the focal plane catcher and thus to allow the study of decays with very short lifetimes. In addition the granularity, combined with tracking, might allows us to track the origin of the detected γ-ray [25]. This tracking allows us to associate an implanted ion with its decay γ-rays (excluding random coincidences with background radiation produced upstream) and, hence, enables long decay times to be studied at high implantation rates. In addition the position information can be used to measure angular correlations and polarizations.

Other detectors to be used within the DESPEC setup include neutron detectors, a total absorbtion spectrometer and fast scintillator detectors for lifetime mesurements. Neutron detectors are particularly important, considering the research interest in the structure of nuclei with high neutron excess. They are designed with the main aim to detect β-delayed neutrons. The variaty of the detectors to be available in conjunction with the implantation/decay and the γ-ray detectors is a particular strength of the DESPEC setup.

5. The low enegy branch and HISPEC and DESPEC coupled together

The HISPEC and DESPEC setups will operate in the low energy branch of the SuperFRS. A sketch of the layout of the low energy cave is shown in figure 6. The layout is dominated, due its size, by the energy buncher [17,18]. The energy buncher, consisting of four dipole magnets, a mono-energetic degrader and focussing elements, will be used to deliver relatively mono-energetic beams [26]. These beams have the disadvantage of worse beam quality, manifesting itself in higher angular and position spread. The main applications of the mono-energetic beams are in experiments where stopping them in a thin layer of matter, such as a gas catcher, is vital. More importantly for HISPEC and DESPEC the first part of the energy buncher, with one dipole magnet, can serve as a high-resolution magnetic spectrometer.

Recoil decay tagging is a powerful technique to study the nuclear structure. It requires the detection of both the prompt radiation at the reaction target and the delayed decay at the final focal plane of the magnetic spectrometer. Therefore, the HISPEC and DESPEC setups have to be able to work together.

The HIPSEC setup can be positioned in two different places (as shown in figure 6.): (i) before the energy buncher to receive beam directly from the SuperFRS, and (ii) after the energy buncher, receiving mono-energetic beams. DESPEC can be positioned in three different places: (i) before the energy buncher, (ii) after the energy buncher, and (iii) after the magnetic spectrometer for recoil decay tagging experiments.

Acknowledgements

HISPEC/DESPEC is a collaboration involving more than 150 scientists from about 50 institutions throughout the world. The full list of participants can be found in ref.[8]. The contributions made by all participants is acknowledged.

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