Vol. 40 (2009) ACTA PHYSICA POLONICA B No 3

# NUCLEAR SPECTROSCOPY STUDIES AT GSI — FROM RISING TO HISPEC/DESPEC*

J. Gerl

GSI, Darmstadt, Germany

(Received December 22, 2008)

Nuclear spectroscopy using radioactive isotope beams requires dedicated set-ups. At the SIS/FRS facility at GSI exotic beams at relativistic energies were employed for Coulomb excitation and secondary fragmentation experiments with the fast beam RISING set-up. Shell evolution far off stability, *pn*-pairing, symmetries and nuclear shapes were studied in nuclei ranging from $^{36}$Ca to $^{136}$Nd. In another Ge-detector configuration a series of $g$-factor experiments was performed. Recently the compact detector arrangement of RISING — providing about 15% full energy efficiency — went into operation. Seniority isomers in medium heavy nuclei at the proton drip line have been investigated as well as new isomers found in neutron rich nuclei, *e.g.* $^{204}$Pt. Most recently the decay properties of $^{100}$Sn were investigated successfully. At future FAIR/GSI the Super-FRS facility within the NUSTAR project will provide an enormously enlarged variety of exotic beams. To fully exploit these beams the HISPEC/DESPEC project aims to develop, build and operate optimized experimental set-ups. Based on the experience with RISING novel particle identification and tracking detectors will be employed. For in-beam $\gamma$ detection AGATA detectors are foreseen as well as a dedicated compact Ge tracking and imaging array for decay experiments. Well before the Super-FRS facility will become operational, detectors developed for HISPEC/DESPEC will be commissioned and employed for experimental campaigns within the PRESPEC project at the FRS facility at GSI.

PACS numbers: 25.70.De, 25.70.Mn, 29.30.–h, 29.30.Kv

## 1. Goals of nuclear spectroscopy with radioactive beams

Nuclear structure physics is confronted with a number of fundamental questions which determine the research priorities in our field. The mission statement of the NUSTAR Collaboration defines clearly the key issues which need to be resolved:

* Presented at the Zakopane Conference on Nuclear Physics, September 1–7, 2008, Zakopane, Poland.

- What are the limits for existence of nuclei?
  - Where are the proton and neutron drip lines situated?
  - Where does the nuclear chart end?
- How does the nuclear force depend on varying proton-to-neutron ratios?
  - What is the isospin dependence of the spin-orbit force?
  - How does shell structure change far away from stability?
- How to explain collective phenomena from individual motion?
  - What are the phases, relevant degrees of freedom, and symmetries of the nuclear many-body system?
- How are complex nuclei built from their basic constituents?
  - What is the effective nucleon–nucleon interaction?
  - How does QCD constrain its parameters?
- Which are the nuclei relevant for astrophysical processes and what are their properties?
  - What is the origin of the heavy elements?

To understand the properties of nuclei it is necessary to establish the interactions between their components, and to determine the arrangements of the nucleons, *i.e.* the structure of the nuclei. This goal is the domain of nuclear spectroscopy. To answer the questions posed above it is necessary to expand our research to exotic nuclei situated far away from the valley of $\beta$ stability. Indeed, recent progress in our understanding of the structure of atomic nuclei is based on the synthesis and study of new species far off stability, evolving from novel experimental methods, as well as new, improved theoretical models of the nucleus.

Accelerators for radioactive ion beams (RIBs) open the possibility to study the structure of nuclei with a large excess of neutrons and enable a whole new range of experiments on exotic nuclei. At GSI the FRS facility delivers RIBs of all elements with typical beam energies of several hundred $A$MeV. However, the employed fragmentation or fast fission processes result generally in rather low beam intensities compared to stable beam accelerators. The planned Super-FRS facility at FAIR will improve this situation, with higher primary beam intensities and larger transmission in particular for fission products. This will shift the borderline of employable isotopes considerably outwards. Nevertheless, close to the border the beam intensities will always be low and the background related to the beam production high.

To address these limitations detector systems with ultimate sensitivity and selectivity are mandatory. The RISING in-beam and decay set-ups constitute current state-of-the-art systems for $\gamma$ spectroscopy at fragmentation RIB facilities. Research and development efforts toward novel detection techniques, new detector materials, advanced electronics, more powerful data processing hardware and software allow continuous improvement of these systems. The effect of improved instrumentation for shifting the borderline of accessible exotic nuclei, respectively subtleness of detectable structure effects, can be as large as or even surpass the impact of a new beam facility. The emerging experimental opportunities, the associated possibilities for nuclear structure physics and the steps towards the future are described in the following sections.

## 2. RISING — achievements and limitations

The RISING Collaboration, including 40 research groups mainly from Europe, has conducted over the last four years campaigns of $\gamma$ spectroscopy experiments making use of the radioactive beams produced with the SIS/FRS facility at GSI, Darmstadt. The RISING set-up [1] is based on the 15 Cluster detectors which originally were part of the EUROBALL array and on charged particle detectors for the identification and tracking of the beam before and after the secondary target. The RISING array is, at the moment, the most efficient $\gamma$-ray detector system coupled to an in flight radioactive beam facility in the world. The physics program is very rich and has produced key experiments.

In the performed experiments the SIS/FRS facility provided secondary beams of exotic isotopes produced via fragmentation or fast fission reaction through the use of relativistic heavy ion beams. The energy of the secondary beams varied between 100 $A$MeV and 600 $A$MeV. For beam intensities of the order of $10^3$–$10^4$ ions/s in-beam $\gamma$-ray spectroscopy was performed using both Coulomb excitation and secondary fragmentation reactions. In the case of very weakly produced ions studies of their decay from isomeric states or $\beta$-decay were possible.

### *2.1. Relativistic in-beam studies*

The fast beam set-up depicted in Fig. 1 was designed to detect $\gamma$-rays emitted by radioactive beams moving at relativistic energies, and being excited via Coulomb excitation or via fragmentation reactions at a secondary target. The Ge Cluster detectors covered a wall at forward angles to take advantage of the Lorentz boost and were placed at 70 cm from the target to minimize the Doppler broadening effect [1]. The overall full energy peak efficiency was 3% at 1.3 MeV. Various types of gas, Si and scintillation detectors were used for the $A$ and $Z$ identification before and behind the secondary target. While the $A$ and $Z$ identification before the secondary target was made using the standard detectors of the FRS set-up [2], for the identification behind the target the CATE calorimeter [3] was constructed, consisting of position sensitive Si detectors for $\Delta E$ and CsI(Tl) scintillators for $E$ measurements. In addition, for some specific measurements the MINIBALL and HECTOR detectors were also included in the set-up. Using this set-up shell evolution far off stability, $pn$-pairing, symmetries and nuclear shapes were studied in nuclei ranging from $^{36}$Ca to $^{136}$Nd.

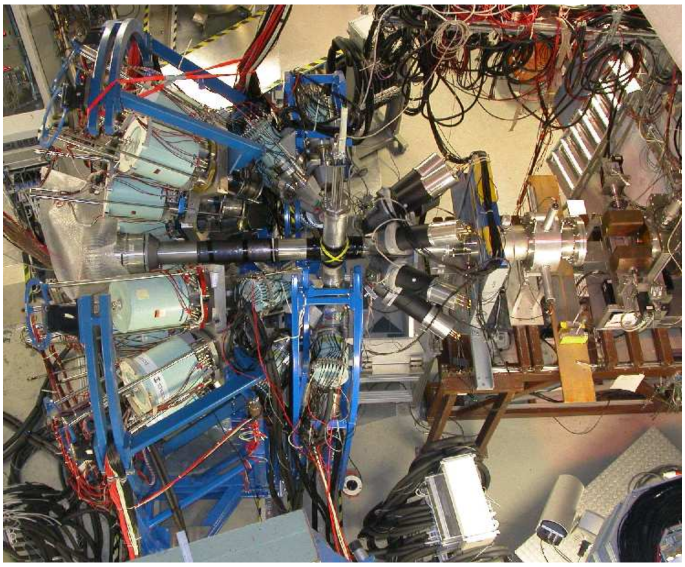

Fig. 1. RISING fast beam set-up.

One example to demonstrate the peculiarities and the potential of such experiments is the determination of the Coulomb energy difference of isobaric analogue states for the mirror nuclei $^{36}$Ca and $^{36}$S [4]. After the initial fragmentation of a beam of $^{40}$Ca the isotope $^{37}$Ca was selected with the FRS and fragmented again on a secondary Be target to populate the nucleus $^{36}$Ca in an excited state. Precise beam tracking, reaction product identification and Doppler correction allowed identifying the decay of the first excited state in $^{36}$Ca. The measured Coulomb energy difference for the $2^+_1$ states of $-276(16)$ keV is about a factor of 5–10 larger than that normally observed for $T = 1$ states. Independently on the employed interaction the use of experimental single particle energies based on experimental values of the $A = 17$, $T = 1/2$ mirrors and empirically including Coulomb and Thomas–Ehrman effects, almost fully accounts for the observed energy difference.

Another example is the relativistic Coulomb excitation experiment performed to populate $2^+$ states in $^{136}$Nd [5]. The isotope was produced by fragmentation of a $^{152}$Sm beam. Despite the rather high secondary beam energy of 126 *A*MeV before the 0.4 g/cm$^2$ thick secondary Au target, the energy resolution of the Doppler corrected $\gamma$ spectrum shown in Fig. 2 and the achieved background suppression are impressive. From the decay of the first $2_1^+$ and second $2_2^+$ states the $B(\mathrm{E2})$ values were deduced. The comparison with the asymmetric rotor model and the Geometrical Collective Model (GCM) yields information on the nuclear shape, namely the $\beta$ and $\gamma$ quadrupole deformation parameters. The chosen GCM potential exhibits a shallow minimum at $\beta_{\mathrm{min}} = 0.225$, $\gamma_{\mathrm{min}} = 20.6°$ with pronounced $\gamma$-softness.

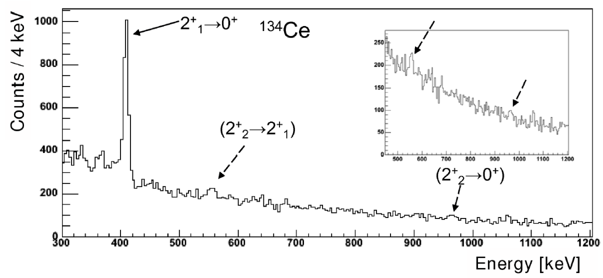


Fig. 2. $^{136}$Nd $\gamma$ spectrum from Coulomb excitation at 126 *A*MeV.

### 2.2. *Advanced decay spectroscopy*

By using the fragment separator to select and transport specific nuclei of interest to the final focal plane of the FRS, decay studies of both isomeric states and following the radioactive decay of the daughter nuclei can be performed with beam intensities well below 1/s. This often allows for the first spectroscopic information on these highly exotic systems.

The detector set-up to track and identify nuclei transported by the FRS to the final focal plane is similar to the one described before. To be able to investigate decay processes the nuclei are implanted in a stopper, which can be in the easiest case a simple aluminum plate. The Ge Cluster detectors in the stopped beam configuration are arranged in a compact $4\pi$ configuration as can be seen in Fig. 3. Providing a full energy efficiency of 11% at 1.3 MeV and 20% at 0.6 MeV, this array is currently the most powerful high-resolution $\gamma$ spectrometer for decay experiments in the world.

In previous set-ups, relying on only a few very efficient detectors, the so-called "prompt flash" effect "blinded" typically the majority of the detectors for the time interval required to electronically process their signals. The

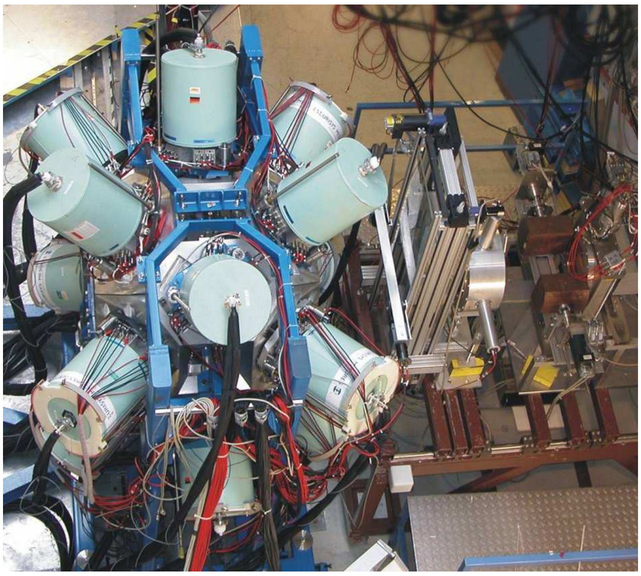

Fig. 3. RISING decay set-up.

RISING array overcomes this problem by its large number of detectors. Losses are reduced to typically 5% clearly providing a major increase in the experimental efficiency.

A goal of RISING is the investigation of $\beta$ decaying isotopes with rates at the final focus of the FRS as small as 1/h and abundances in the produced beam cocktail in the per mile range. To study their radioactive decay thus requires a detection set-up with optimal sensitivity and selectivity to detect wanted decay $\gamma$-rays among the overwhelming background radiation from other isotopes and the environment. For that purpose an active catcher has been developed for RISING which allows correlation of $\beta$-decays with implanted radioactive mother nuclei on an event-by-event basis. The active catcher consists of three layers of three horizontally aligned Double Sided Silicon Strip Detectors (1 mm thick, $5 \times 5\,\mathrm{cm}^2$, 16 horizontal and vertical strips) with semi-logarithmic pre-amplifiers providing a linear response in a wide energy interval (10 MeV–3 GeV) [6]. The large number of 768 pixels enable rather long correlation times, and in fact enabled clean selection of isotopes with $\beta$-decay lifetimes as long as 30 s!

Many experiments are still under analysis, like *e.g.* the recently performed investigation of the decay properties of $^{100}$Sn and its neighbours. Several articles in this volume deal with results of recent RISING decay experiments. Therefore again only examples highlighting features and possibilities of RISING are presented here.

The region below $^{208}$Pb is an important area where only little structural information is available. Systematic RISING studies recently produced a wealth of new data, *e.g.* essential in producing more accurate predictions on the properties of the $N = 126$ r-process path-nuclei. A remarkable finding was an excited state in the neutron-rich $N = 126$ $^{205}$Au nucleus which has been identified through conversion electron spectroscopy using the active stopper [7]. The new state has an excitation energy of 911 keV and a lifetime of $\tau = 8(2)$ s. It corresponds to the $\pi h^{-1}_{11/2}$ single proton-hole excitation and decays directly into the $\pi d^{-1}_{3/2}$ ground-state. The energy of this excited state is in good agreement with shell-model calculations.

The first identification of a $10^+$ isomeric state at 6457 keV in the nucleus $^{54}$Ni [8] gave relevant information on isospin symmetry effects. This new state has an isobaric analog in $^{54}$Fe and can be interpreted in terms of isospin-dependent shell-model calculations. For this unbound state in $^{54}$Ni a clear evidence was found for a discrete proton decay branch into the first excited state of the daughter $^{53}$Co with angular momentum $l = 5$. This decay is the first of its kind observed following projectile fragmentation reactions. A search for new isomers in $^{53}$Co was also made and indeed evidence of decay from the yrast $3/2^-$ state was found [9]. This isomer was populated by means of secondary nuclear reactions of a $^{54}$Ni fragment beam during its stopping process. The experimental findings are explained in the framework of large-scale spherical shell model calculations in conjunction with isospin symmetry-breaking residual interactions for the $A = 53$, $T_z = \pm 1/2$ mirror nuclei $^{53}$Co and $^{53}$Fe.

Particular effort is being made to shed light on the shape evolution along the $N = Z$ line between the doubly-magic systems $^{56}$Ni and $^{100}$Sn. In this connection the low-lying structure of the self-conjugate ($N = Z$) nuclei $^{82}$Nb and $^{86}$Tc were investigated using isomer decay spectroscopy following the fragmentation of $^{107}$Ag [10]. These nuclei represent the heaviest odd–odd $N = Z$ nuclei in which internal decays have been identified to date. The results support a preference for $T = 1$ states in $T_z = 0$ odd–odd nuclei at low excitation energies associated with a $T = 1$ neutron–proton pairing gap. Comparison with Projected Shell Model calculations suggests that the decay in $^{82}$Nb may be interpreted as an isospin-changing $K$ isomer.

The Time Differential Perturbed Angular Distribution (TDPAD) method is most suited to measure the $g$-factor of microsecond isomeric states. Already for medium heavy isotopes the beam energy needs to be $> 300A$MeV, uniquely available at GSI to obtain fully stripped ions mandatory for spin-aligned ensembles of isomers implanted in a suitable stopper that is placed in a static magnetic field. The series of $g$-RISING experiments demonstrating the feasibility of the method and providing new experimental data has been reported earlier [10] and is thus mentioned her only for completeness.

### 3. PRESPEC — the next steps

The RISING project will be finishing in August 2009 and is planned to be superseded by PRESPEC, an initiative to continue the successful experimental programme of high resolution $\gamma$-spectroscopic studies employing fast and stopped radioactive beams from the FRS. At the same time PRESPEC is the platform to commission new instrumentation developed and built for the future HISPEC and DESPEC project at the Super-FRS of the FAIR facility. Early implementations of the new detection systems will be used for PRESPEC experiments as they become available taking advantage of the novel techniques and methodologies. This approach allows for a continuous upgrade of the capabilities of the detection systems thereby steadily shifting the frontier of doable experiments towards more exotic nuclei respectively more detailed structure studies.

Like with RISING dedicated in-beam and decay campaigns are planned. The first proposed experimental configuration will comprise the Ge Cluster and MINIBALL detectors as well as a new fragment tracking and identification device, the Lund–York–Cologne Calorimeter Array (LYCCA), being developed for implementation at HISPEC. The early-implementation of LYCCA will be available from 2010, and it is going to comprise a combination of Si strip $\Delta E$ detectors, CsI(Tl) scintillators, and ultra-fast plastic and CVD diamond ToF detectors. A plunger device adopted to the wide beam spot size of the FRS beams will be available for lifetime measurements. In addition a segmented plastic detector at the mid-focal plane of the FRS and new digital electronics for the MUSIC $\Delta E$ detectors at the final focus will allow increasing the secondary beam intensity by one order of magnitude.

In a later phase of PRESPEC the $\gamma$-tracking array AGATA [11] (equipped with the then available number of detector units) will increase the detection sensitivity by at least another order of magnitude. In-between another decay experiment campaign is planned, comprising the AIDA active stopper array, and neutron detection systems, all currently under development for DESPEC.

Along with the anticipated upgrade of primary beam intensity at GSI, PRESPEC will provide unique capabilities, to be exploited by the European nuclear structure community over the coming years continuing the successful program of the RISING project. A flavour of the investigations currently under discussion for the first PRESPEC in-beam campaign is given in the following.

The evolution of shell closures and the ordering of quantum states with proton and neutron number is one of the most crucial questions in contemporary nuclear science. For instance in the $fp$ shell most of the shell-model effective interactions predict a subshell closure at $N = 32$ for Ca nuclei, which has been confirmed experimentally, and a new shell closure at $N = 34$ for neutron-rich nuclides. To investigate it the energy of the first excited states in these isotopes needs to be measured.

From recent decay studies a lot of new transitions have been found for exotic nuclei with $Z < 28$ and $N > 40$. However, the spin-parity assignments are ambiguous and mainly guided by deformed and spherical shell model expectations. Here complementary in-beam studies, providing *e.g.* $B(\mathrm{E2})$, respectively lifetime data and $g$-factors will be helpful. The same holds for the $N = 82$ shell closure, and its possible quenching, below $^{132}$Sn.

Coulomb excitation and lifetime measurements following secondary fragmentation will provide insight into collective features of exotic nuclei. Neutron-rich Zr isotopes could be a test case to study dynamical symmetries. On the other side of the chart of nuclides the investigation of very light Xe and Te isotopes may shed light to the recently claimed enhanced collectivity.

The exchange symmetry between neutrons and protons is one of the most fundamental symmetries in nature, resulting in the powerful concept of nuclear isospin. PRESPEC aims to explore the isospin degree of freedom by detailed spectroscopy of excited states of exotic $Z > N$ nuclei. For that purpose exotic proton-rich fragment beams will be studied using secondary fragmentation or Coulomb excitation at the PRESPEC target. Particular interest lies in understanding how the concept of isospin symmetry begins to break down as the drip-line is approached.

An interesting question in nuclear structure physics is related to the nature of triaxial deformation in atomic nuclei. In particular in the mass $A = 100$ region chiral twin bands have been observed in odd–odd nuclei. The question whether the stability of this chiral geometry (*i.e.* rigid triaxial shapes) arises from the coupling of the valence particles or it is a feature of the even–even core still remains unclear. Therefore, the nature of the even–even cores needs to be investigated. For that purpose it is planned to examining the evolution of the decays from the first and second $2^+$ states from the island of chirality in the mass $A = 100$ region towards neutron-rich nuclei where more $\gamma$-rigid shapes are expected.

Another interesting question is how the E1 strength evolves for nuclei far from stability for neutron- and proton-rich nuclei. This is one of the key topics in nuclear structure since it provides information on the properties of neutron/proton skins and, consequently, on the symmetry energy. High-resolution measurements are planned to investigate the structure of the low lying dipole strength in light to medium heavy exotic nuclei.

## 4. HISPEC/DESPEC — plans and prospects

At future FAIR/GSI [12] the Super-FRS facility [13] within the NUSTAR project [14] will provide an enormously enlarged variety of exotic beams. To fully exploit these beams lasting detection deficiencies have to be solved. They result from still limited beam intensity, particularly for the most exotic nuclei, a wide range of beam velocities (from stopped to $v/c \sim 0.5$), high $\gamma$-ray and particle background and $\gamma$-ray multiplicities up to $M \leq 30$, which are typical characteristics of the reactions. The HISPEC/DESPEC [15,16] project aims to develop, build and operate optimized experimental set-ups. Based on the experience with RISING novel particle identification and tracking detectors will be employed. For in-beam $\gamma$ detection AGATA detectors are foreseen as well as a dedicated compact Ge tracking and imaging array for decay experiments. In addition, a suite of ancillary detectors is planned to complete the experimental set-ups. Well before the Super-FRS facility will become operational, detectors developed for HISPEC/DESPEC will be commissioned and employed for experimental campaigns at the FRS facility at GSI as they become available. This evolutionary approach with continuously improving experimental possibilities allows exploring increasingly remote areas of the nuclear landscape and enables more and more detailed structure studies of less exotic nuclei.

### *4.1. DESPEC*

The advantage of the decay experiments is that they can be based on a relatively small number of events. A unique feature of the Super-FRS will be the access to regions where the waiting points for the r-process occur. For the understanding of the r-process nucleo-synthesis of heavy elements in supernova explosions one needs to know the $\beta$-decay half-life, the neutron branching ratios and the neutron (or two-neutron) separation energy of these nuclei. The DESPEC set-up will enable to measure the first two quantities. If the number of decays is sufficiently high, detailed spectroscopy will be possible and then questions such as isospin symmetry can be tested in mirror nuclei or the long standing Gamow–Teller quenching problem in $\beta$-decay can be addressed. On a more fundamental level superallowed Fermi transitions in odd–odd $N = Z$ nuclei can be used to explore issues such as the unitarity of the CKM matrix in the Standard Model of electroweak interactions. For the most exotic nuclei we can expect some unusual decay modes such as $\beta$ delayed multi-neutron emission, $\beta$ delayed fission, or even direct neutron radioactivity. Another very important aspect of DESPEC is the possibility to study the decay properties of isomeric levels in nuclei which survive the flight time from the moment of production until the time of arrival to our set-up.

All of the experiments anticipated at DESPEC involve implantation of the ions in an active stopper prior to the decay. The foreseen AIDA detector will be highly segmented, which allows to correlate in time and space the signal of the initial pulse from implantation of the heavy ion with the signal produced in the same detector in the subsequent $\beta$-decay. Neutron and high resolution $\gamma$-ray detectors in a compact arrangement around the active stopper in a highly flexible and modular geometry will be at the heart of this set-up. The DESPEC Ge array will be the first $\gamma$ tracking array with imaging capability, allowing to determine the origin of $\gamma$-rays. This enables the selection of $\gamma$-rays emitted by implanted nuclei and in particular the suppression of the dominant background radiation. Complementary measurements using a Total Absorption Spectrometer and measurements of nuclear $g$-factors and quadrupole moments as well as level half-lives are also foreseen.

### *4.2. HISPEC*

The second fundamental pillar to study the properties of the nuclei is by means of nuclear reactions. They have the advantage of their high flexibility. By selecting a suitable combination of projectile, target, and beam energy, one can obtain a variety of results ranging from the reaction products to the character of the states that are populated. At the HISPEC set-up these kind of studies can be carried out with radioactive beams of intermediate energies, or at energies around the Coulomb barrier with slowed down beams.

Single step Coulomb excitations and fragmentation reactions at intermediate energies as well as inelastic scattering, transfer reactions and fusion evaporation reactions at lower energies will provide information about transition probabilities, single particle spectroscopic factors, high spin states, *etc.* By observing the single particle or collective vibrational or rotational character of the states, we can conclude about basic properties of the nucleus such as the shape. High resolution Ge detectors will be used to measure the $\gamma$ transitions of the levels populated. The HISPEC set-up has at its core AGATA, the next generation $\gamma$-ray tracking array, with a resolving power exceeding the presently available Ge-arrays by orders of magnitude. In addition, the set-up will comprise beam tracking and identification detectors placed before and behind the secondary target, charged particle detectors, a plunger, a magnetic spectrometer and other ancillary detectors.

## REFERENCES


[1] H.J. Wollersheim *et al., Nucl. Instrum. Methods* **A537**, 637 (2005).

[2] H. Geissel *et al., Nucl. Instrum. Methods* **B70**, 286 (1992).

[3] R. Lozeva *et al., Nucl. Instrum. Methods* **A562**, 298 (2006).

[4] P. Doornenbal *et al., Phys. Lett.* **B647**, 237 (2007).

[5] T. Saito *et al., Phys. Lett.* **B669**, 19 (2008).

[6] R. Kumar *et al., Nucl. Instrum. Methods* **A**, in print.

[7] Zs. Podolyak *et al.*, submitted to *Phys. Lett.* **B**.

[8] D. Rudolph *et al., Phys. Rev.* **C78**, 021301 (2008).

[9] D. Rudolph *et al., Eur. Phys. J.* **A36**, 131 (2008).

[10] G. Neyens *et al., Acta Phys. Pol. B* **38**, 1237 (2007).

[11] AGATA Technical Proposal, Eds. J. Gerl and W. Korten, GSI Darmstadt 2001.

[12] FAIR Conceptual Design Report, GSI Darmstadt 2001.

[13] H. Geissel *et al., Nucl. Instrum. Methods* **B204**, 71 (2003).

[14] B. Rubio, T. Nilsson, *Nucl. Phys. News* **16(3)**, 9 (2006).

[15] Zs. Podolyak, *Int. J. Mod. Phys.* **E15**, 1967 (2006).

[16] B. Rubio, *Int. J. Mod. Phys.* **E15**, 1979 (2006).