PRESPEC – GAMMA-SPECTROSCOPY ON THE WAY TOWARDS NUSTAR

HANS-JÜRGEN WOLLERSHEIM

GSI Helmholtzzentrum für Schwerionenforschung mbH,
Planckstrasse 1, D-64291 Darmstadt, Germany
h.j.wollersheim@gsi.de

On behalf of the PreSPEC/AGATA collaboration

The new PreSPEC project is aimed at nuclear structure and reaction studies using radioactive isotope beams. At the SIS/FRS facility at GSI exotic beams at relativistic energies were employed for Coulomb excitation and secondary fragmentation experiments. High-resolution gamma-ray spectroscopy is the main tool to investigate the shell evolution far off stability, proton-neutron interaction, symmetries and nuclear shapes. Compared to the former RISING set-up an advanced particle (LYCCA) and γ-ray (AGATA) detection system are used. At the future FAIR facility, these tools will be employed by the High-resolution In-flight SPECtroscopy (HISPEC) project. The improvements in the experimental set-ups, together with the opportunities to be opened, are discussed.

1. Introduction

In the next few years the new international accelerator facility FAIR (Facility for Antiproton and Ion Research [7]), one of the largest research projects worldwide, will be erected at GSI (Helmholtzzentrum für Schwerionenforschung [9]). At FAIR an unprecedented variety of experiments will be carried out to allow new insights into the structure of matter and the evolution of the universe from Big Bang to the present. The production of chemical elements heavier than iron are assumed to originate from collapsing stars or stellar collisions. The underlying processes depend on the nuclear forces and symmetries in rare isotopes. We will get information on the force acting between the nucleons inside the nucleus, with special emphasis on systems with exotic proton-to-neutron ratios: both proton-rich nuclei and neutron-rich nuclei. In extreme neutron-rich nuclei radical changes in their structure are expected with the possible disappearance of the classical shell gaps and magic numbers and the appearance of new ones. The nuclear structure community is heavily committed to the future NUSTAR (Nuclear Structure, Astrophysics and Reactions [12]) program of in-flight (HISPEC) and decay (DESPEC) γ-ray spectroscopy of highly exotic nuclei produced from the SUPER-FRS (FRagment Separator). As a pre-cursor of both high-resolution set-ups the PreSPEC project [13] was established, which builds on the very successful RISING (Rare Isotope Spectroscopic Investigation at GSI) campaigns.

The RISING project [19] started in 2003 with a series of in-beam experiments employing rare isotope beams (RIB) at relativistic energies. It combined the former EUROBALL Ge-Cluster detectors and the fragment separator FRS [8] at GSI for high-resolution γ-ray spectroscopy measurements. In the fast-beam RISING campaign, relativistic Coulomb excitation [1, 2, 21], two-step fragmentation reactions [4] and virtual photon scattering [17] were successfully used. Sufficient experience was gained from these to undertake this new PreSPEC campaign. This contribution focuses on the current spectroscopy activities at GSI, i.e. the PreSPEC project with an advanced particle (LYCCA) and γ-ray (AGATA) detection system as compared to the RISING set-up.

2. The PreSPEC experiment

The four fundamental pillars of the PreSPEC project are the intense ion beams of the GSI accelerator facility, the fragment separator FRS for providing beams of radioactive ions, its advanced heavy ion detection system, LYCCA (Lund-York-Cologne Calorimeter) [15], which allows the identification of the exotic fragments with respect to their element and mass numbers and AGATA (Advanced Gamma Tracking Array) [5] with a resolving power hugely exceeding the present available Ge-arrays.

2.1. *SIS/FRS facility*

In-flight γ-ray spectroscopy experiments at GSI start with a very intense primary beam of stable isotopes delivered by the SIS heavy-ion synchrotron. The present maximum beam intensity is ~$10^{10}s^{-1}$ for medium heavy ions, e.g. ^{129}Xe, and ~$2 \cdot 10^9 s^{-1}$ for ^{208}Pb or ^{238}U. This primary beam impinges on a production target at a very high energy, typically 500 to 1000 AMeV. The target is in most cases a ^{9}Be (thickness ~$1g/cm^2 \equiv 6.7 \cdot 10^{22}$ target nuclei/cm^2) or ^{208}Pb (thickness ~$1g/cm^2 \equiv 2.9 \cdot 10^{21}$ target nuclei/cm^2), which is located at the entrance of the GSI fragment separator FRS. This way, a broad spectrum of radioactive species is produced by means of fragmentation or induced fission reactions. For fragmentation reactions the cross sections are taken from the on-line EPAX-program [6], while experimental data are available for nuclear and electromagnetic fission yields [8].

The FRS [FRS] is a zero-degree magnetic spectrometer and consists of four dipole stages and an aluminum degrader at the intermediate focal plane (S2), which provides high-energy, spatially separated isotopically pure exotic beams of all elements up to uranium. The fragments of interest are selected and transmitted via their magnetic rigidity, Bρ, and energy loss, ΔE, in the degrader, the so-called Bρ-ΔE-Bρ method. They are identified in-flight on an event-by-event basis using their magnetic rigidity Bρ, their time of flight between two scintillation detectors positioned at the middle (S2) and final (S4) focal planes and their energy loss measured with two multi-sampling ionization chambers (MUSIC). Corrections for different trajectories through the FRS are performed based on position measurements with pairs of time-projection chambers (TPC). Compared to the fast-beam RISING campaign, the FRS tracking detectors provide a significant improvement of the accessible rates at which an event-by-event tracking can be performed.

At the final focal plane (S4) a 32x32-strip, 58x58 mm^2 double-sided silicon-strip detector (DSSSD) serves to determine the position of the beam particles at the secondary target. For energies of 100 AMeV the spatial profile of the fragments beam show typically a width of 6cm (FWHM) in the dispersive horizontal plane X and about 4cm (FWHM) on the vertical axis Y. The secondary target material is usually gold for Coulomb excitation and beryllium for fragmentation or particle knockout reactions. Thanks to the high secondary beam energy, rather thick targets of 200mg/cm^2 to 500mg/cm^2 can be used to reach the necessary luminosity for in-beam γ-ray spectroscopy experiments and keeping the angular straggling of the reaction products as low as 5-10mrad.

2.2. *Identification after the secondary target*

For the identification of isotopes following different types of reactions in the secondary target, the LYCCA (Lund-York-Cologne Calorimeter Array) detector array [15] will be used which provides major upgrades with respect to the previous calorimeter device, CATE [11]. According to simulations [16], this system will allow the identification of ions up to mass of A~100. The LYCCA array consists of 16 ΔE-E telescopes and it will measure the time-of-flight between the secondary reaction target and the array separated by about 3.4m. Each telescope comprises a DSSSD wafer as described above followed by an array of nine CsI detectors. These have photodiode readout and are 19x19 mm^2 in size and either 11mm or 33mm thick.

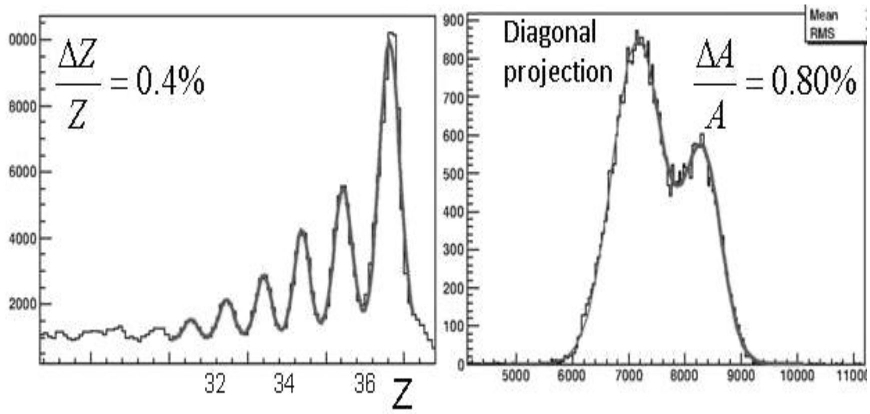

Figure 1. Projectile fragments are identified after the secondary target using the LYCCA array [15]. In the present experiment a stable ^{84}Kr beam impinges on a primary ^{9}Be target to produce different Br isotopes. The Z-resolution (left) of the displayed data [18] is slightly worse than obtained with the FRS detectors. The fragment masses of ^{83}Br and ^{84}Br are clearly discriminated.

The energy loss (DSSSD, ΔE/E≤1% intrinsic) and residual energy (CsI, ΔE/E≤0.5% intrinsic) signals provide the Z resolution. The time-of-flight (ToF) system provides a major new capability for in-beam spectroscopy – giving mass information. For ToF measurements ultra fast scintillators are used: in front of the LYCCA telescopes, a large-area plastic scintillator (BC-420) is mounted using readout with 32 small ultrafast PMTs (Hamamatsu R7400U). The ToF-start is another similar plastic detector, located in close vicinity to the secondary target. The timing features of LYCCA are summarized in [10]. The present value of the intrinsic timing resolution is $\Delta t \leq 50ps$.

Some results showing the LYCCA performance are given in Fig.1. For the $^{84}Kr+^{9}Be$ fragmentation one obtains a slightly worse Z-resolution than measured with the FRS detectors. It also shows the separation between ^{83}Br and ^{84}Br, indicating that discrimination can be achieved in this mass region. In addition a large-area PC-CVD diamond detector (made of 2x6 cm^2 wafers) is in development to be used as ToF system in future experiments.

2.3. ***The Gamma-Ray Array***

Another main difference as compared to previous in-flight campaigns at the FRS, is the use of AGATA cluster detectors made from segmented Germanium crystals that are placed around the secondary target at S4. In the beginning 3 double and 5 triple AGATA detectors were available, each comprising two or three 36-fold segmented HPGe crystals; these numbers will increase during the campaign. In addition, the HECTOR array consisting of large scintillation detectors (BaF_2 and $LaBr_3$) is used to measure high-energy γ-rays.

The Advanced GAmma Tracking Array [14] is an European project to develop and operate the next generation γ-ray spectrometer. The array is composed of so-called double and triple detectors. In combination with sophisticated pulse-shape analysis algorithms 3D position resolution of all interactions within the active volume is achieved with an accuracy of ~5mm. Tracking algorithms allow reconstructing the (total) γ-ray energy and emission direction from the individual interactions.

Because of the high fragment velocity β the measured γ-ray energy E_γ appears shifted with respect to the γ-ray energy at rest $E_{\gamma 0}$. The accuracy with which the original γ-ray energy can be determined is dominated by the uncertainty in the determination of the angle ϑ_γ and the uncertainty in measuring the fragment velocity β at the moment of γ-ray emission. Fig.2.2 shows the comparison between RISING ($\Delta\vartheta_\gamma = 8^0$) and AGATA ($\Delta\vartheta_\gamma = 1^0$) for a target-array distance of 23.5cm. For very short-lived states in the pico-second range the expected γ-ray energy resolution $\Delta E_{\gamma 0}/E_{\gamma 0}$ depends also on the fragment velocity β. Since rather thick targets are used, the fragments may decay within the target during the slowing down process.

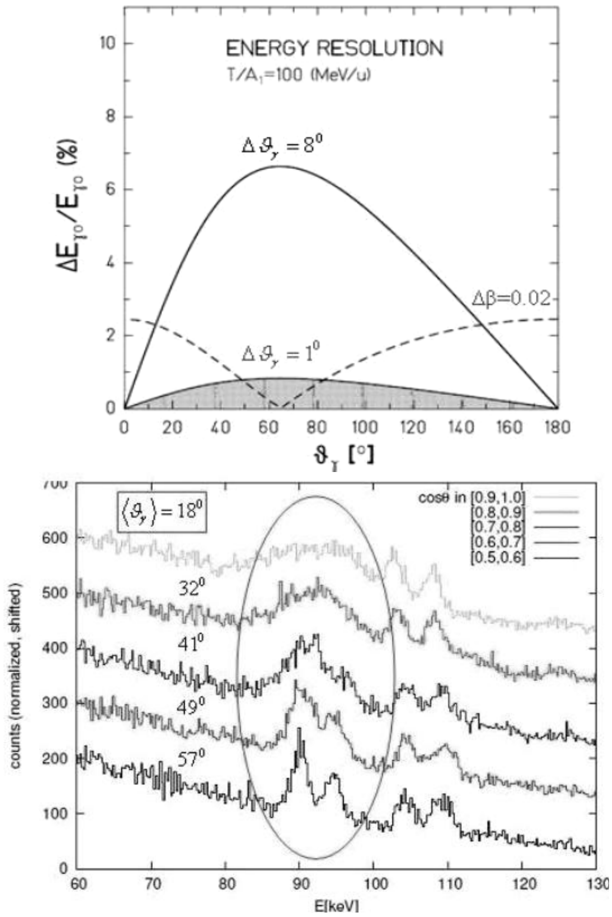

Figure 2. The expected γ-ray energy resolution $\Delta E_{\gamma 0}/E_{\gamma 0}$ as a function of the laboratory angle ϑ_γ for a bombarding energy of 100 AMeV. For the Doppler broadening an opening angle of $\Delta\vartheta_\gamma = 8^0$ (RISING) and $\Delta\vartheta_\gamma = 1^0$ (AGATA) and a spread in the beam velovity of Δβ=2% is assumed (Up). Doppler-corrected X-ray spectra [14] of ^{238}U impinging on ^{9}Be (700mg/cm^2) at 183 AMeV for different γ-ray angles (Down).

During the commissioning of the AGATA detectors $K\alpha_1$ and $K\alpha_2$ X-ray transitions (τ~10-^{17}s) were detected for ^{238}U impinging on a ^{9}Be target (700mg/cm^2) at a beam energy of 183 AMeV. Doppler-corrected X-ray spectra [14] are depicted in Fig.2.2 for different ϑ_γ angles. One observes a better energy resolution for angles close to $\vartheta_\gamma = 60^0$. Since the secondary target can be shifted from 23.5cm to 13.5cm, the AGATA configuration can be optimized for good energy resolution (5-8keV at 1MeV) and keeping the photopeak efficiency high (~10%). Further details of the optimal use of AGATA for in-flight measurements at relativistic beam energies are reported in [3].

The fast beam PreSPEC experiments with the particle detection system LYCCA and the high γ-ray sensitivity of the AGATA array will increase our nuclear microscope by about two orders of magnitude before the very intense beams of the FAIR facility will become available. In first experiments nuclei close to ^{132}Sn and ^{208}Pb have been investigated via electromagnetic excitation and knockout reactions to compare their properties with the nuclear shell model. To exploit most exotic nuclei many key instrumentations are developed and commissioned especially for fragmentation facility, i.e. a new Cologne plunger for lifetime measurements and a liquid hydrogen target. Hydrogen-induced reactions offer a large selectivity: nuclear collectivity can be studies from (p,p′) inelastic scattering, the fragment wave-function can be reliably extracted from (p,pn) and (p,2p) knockout reactions, while two-nucleon knockout is expected to be sensitive to two-body correlations within the nucleus.

References

1. Banu A., ^{108}Sn studied with intermediate-energy Coulomb excitation, *Phys. Rev* **C72**, 061305(R) (2005).
2. Bürger A. et al., Relativistic Coulomb excitation of neutron-rich ^{54,56,58}Cr: On the pathway of magicity from N=40 to N=32, *Phys. Lett.* **B622**, 29 (2005).
3. Domingo-Pardo C. et al., Conceptual design and performance study for the first implementation of AGATA at the in-flight RIB facility of GSI, *Nucl. Instr. Meth*. **A694**, 297 (2012).
4. Doornenba P. et al., The T=2 mirrors ^{36}Ca and ^{36}S: A test for isospin symmetry of shell gaps at the driplines, *Phys. Lett.* **B647**, 237 (2007).
5. Duchene G. et al., AGATA – Advanced Gamma Tracking Array, *Nucl. Instr. Meth.* **A668**, 26 (2012).
6. An Empirical Parametrization of Projectile-Fragmentation Cross Sections. www-wnt.gsi.de/hellstr/asp/gsi/epaxv21m.asp

7. Facility for Antiproton and Ion Research, www.gsi.de/forschung_beschleuniger/fair.htm www-linux.gsi.de/~wolle/EB_at_GSI/FRS/PAPERS/cross-section-1.pdf
8. H. Geissel et al., The GSI projectile fragment separator: a versatile magnetic system for relativistic heavy ions, *Nucl. Instr. Meth*. **B70**, 286 (1992).
9. Helmholtzzentrum für Schwerionenforschung, www.gsi.de/portrait
10. R. Hoischen et al., Fast timing with plastic scintillators for in-beam heavy-ion spectroscopy, *Nucl. Instr. Meth.* **A654**, 354 (2011).
11. R. Lozeva et al., A novel calorimeter telescope for identification of relativistic heavy-ion reaction channels, *Nucl. Instr. Meth.* **A562**, 298 (2006).
12. Nuclear Structure, Astrophysics and Reaction, www.gsi.de/forschung/fair_experiments/NUSTAR
13. www-linux.gsi.de/~wolle/PreSPEC.
14. M. Reese et al., AGATA-week, Darmstadt. (2012).
15. D. Rudolph et al., LYCCA technical report, FAIR TAC HISPEC/ DESPEC. (2010).
16. M.J. Taylor et al., A new simulation package to model detector systems with fragmentation reactions and ion separators: Application to the LYCCA-0 system, *Nucl. Instr. Meth.* **A606**, 589 (2009).
17. O. Wieland et al., Search for the Pygmy Dipole Resonance in ^{68}Ni at 600 MeV/nucleon, *Phys. Rev. Lett.* **102**, 092502 (2009).
18. A. Wendt PhD thesis and J. Taprogge, Diploma thesis, University of Cologne. (2012).
19. H.J. Wollersheim et al., Rare Isotope Investigation at GSI using γ-ray spectroscopy at relativistic energies, *Nucl. Instr. Meth.* **A537**, 637 (2005).