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Pietralla, N.; Reese, M.; Cortes, M.L.; Ameil, F.; Bazzacco, D.; Bentley, M.A.; Boutachkov, P.; Domingo-Pardo, C.; Gadea, A.; Gerl, J.; Goel, N.; Golubev, Pavel; Górska, M.; Guastalla, G.; Habermann, T.; Kojouharov, I.; Korten, W.; Merchán, E.; Pietri, S.; Ralet, D.; Reiter, P.; Rudolph, Dirk; Schaffner, H.; Singh, P.P.; Wieland, O.; Wollersheim, H.J.; Collaboration, the PreSPEC-AGATA

Published in:
EPJ Web of Conferences

DOI:
10.1051/epjconf/20146602083

2014

EPJ Web of Conferences **66**, 02083 (2014)
DOI: 10.1051/epjconf/20146602083

On the Road to FAIR: 1st Operation of AGATA in PreSPEC at GSI

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Abstract. The Facility for Antiproton and Ion Research (FAIR), under construction at Darmstadt will provide intense relativistic beams of exotic nuclei at its Superconducting-FRagment Separator. High-resolution in-beam γ-ray spectroscopy will be performed in the HISPEC experiment, using the European Advanced GAmma-ray Tracking Array (AGATA). The PreSPEC-AGATA campaign is the predecessor of HISPEC and runs from 2012 to 2014 at GSI Helmholtzzentrum für Schwerionenforschung GmbH. Up to 19 AGATA modules were used at GSI's FRagment Separator in 2012. We report on the status of the experiment including preliminary results from performance commissioning.

1 Introduction

The Facility for Antiproton and Ion Research (FAIR) is under construction next to the campus of the GSI Helmholtzzentrum für Schwerionenforschung Gmbh. As one of the major nuclear research facilities in the world, it will provide exotic ion beams of unprecedented quality and intensity for a rich variety of new and unique experiments for fundamental research. One of the four experimental pillars of FAIR, making use of radioactive ion beams from Super-FRS, is called NUSTAR: NUclear STructure, Astrophysics and Reactions. Spectroscopic nuclear structure investigations will be done at the Low Energy Branch (LEB) of the Super-FRS. The HISPEC experiment is dedicated to high-resolution in-beam γ-ray spectroscopy with exotic, relativistic ion beams. Similar experiments were already performed at GSI during the RISING [1] fast-beam campaign, later-on continued in the early PreSPEC campaign during 2010 and 2011 (see, *e.g.*, Ref. [2]), and are ongoing as the PreSPEC-AGATA campaign with AGATA [3] detectors until 2014.

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2 The PreSPEC-AGATA Setup

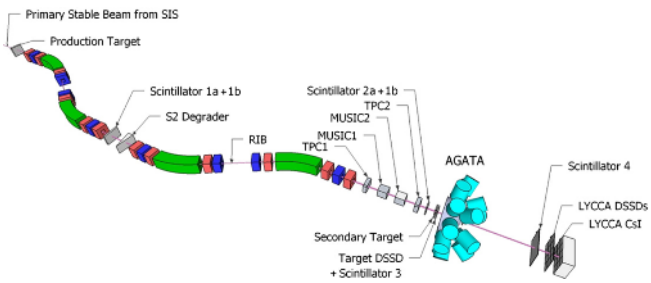

Figure 1. PreSPEC-AGATA experimental setup, taken from [4], showing the FRS [5] and LYCCA [6] with their respective detectors, together with the AGATA [3] spectrometer. See text for details.

In-beam γ-ray spectroscopy with exotic beams faces a number of challenges. First, the incoming particle species must be selected and identified. After reaction on the secondary target, the outgoing particle must be identified and the scattering angle determined. Due to the relativistic velocities of the particles, the emitted radiation is heavily Doppler shifted. To correct the shift properly, information on the velocity of the outgoing particle and on the angle at which radiation is emitted is needed.

The schematic view of the experimental setup at GSI is shown in Fig. 1: A high energy primary beam from the SIS18 synchrotron impinges on a primary production target, producing a cocktail beam of fragments. The particle selection and identification of the incoming ions is done with the FRS [5], which is based on the $B\rho$-ΔE-$B\rho$ technique and identifies them event-by-event by measuring the trajectory, energy-loss and velocity. Selected ions interact with a secondary target, inducing the nuclear reaction of interest. The calorimeter telescope LYCCA [6] tracks and identifies the charge and mass of the outgoing fragments. Double sided silicon strip detectors (DSSSD) are used as tracking and energy loss detectors. One is located at the target position, mainly for tracking, and 16 are at the Wall position in front of 144 CsI(Tl) detectors. Wall DSSSD and CsI(Tl) detectors form a large ΔE-E telescope that is used for ejectile charge identification. Ejectile masses are determined by the LYCCA time-of-flight system using fast scintillators [7].

AGATA [3] is an array of 36-fold segmented HPGe-detectors. It provides the highest possible energy resolution and sensitivity together with a high spatial resolution of incident γ-rays, by means of the novel technique of pulse shape analysis (PSA) and γ-ray tracking. The spatial resolution of AGATA is a major improvement over the Euroball array, because the large solid angle of the Euroball clusters was one of the limiting factors to the energy resolution of the Doppler corrected γ spectra. In consequence, AGATA detectors can be placed much closer to the target where their efficiency is increased. HECTOR+ [8], an array of large volume BaF2 and LaBr3(Ce) fast scinitllators can be used for spectroscopy in addition to AGATA.

3 Commissioning Experiments and Performance of the Setup

The technical commissioning of the setup, i.e. detector elements, front-end electronics, data acquisition and analysis software, has been done with parasitic beams of ^{54}Ti, ^{136}Xe and ^{238}U ions. X-rays of ^{136}Xe and ^{238}U could be used to show quickly that particle tracking and identification with LYCCA is working, and that the Doppler correction algorithms for γ rays is correct (Fig. 2). In order to determine the efficiency and resolution of the setup, a performance commissioning run was conducted using a primary beam of ^{80}Kr ions at energies of around 150 MeV per nucleon at the secondary target. A 1 mg/cm^2 thick beryllium target was used to induce fragmentation reactions of the ^{80}Kr ion beam and a 400 mg/cm^2 thick gold target generated Coulomb excitation reactions. Data analysis is still ongoing, while preliminary results are presented here. Fig. 3 shows the charge identification obtained with

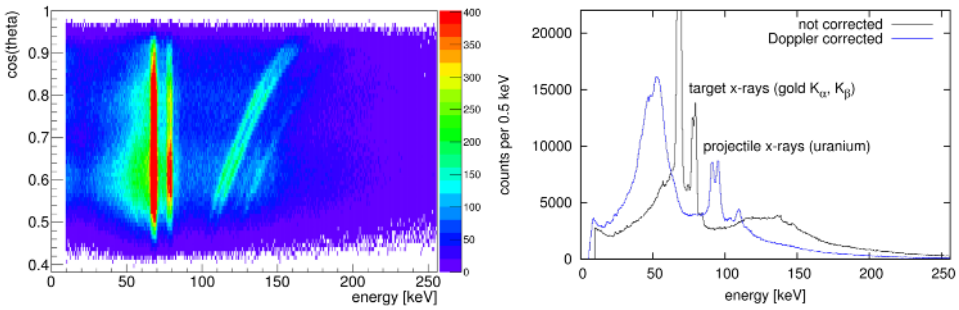

Figure 2. X-ray energy spectra emitted from a gold foil when bombarded by a beam of uranium ions at kinetic energy of 183 MeV per nucleon. Left: Photon energy detected by AGATA vs the cosine of the emission angle, showing the unique feature of continuous distribution in the polar angle. X rays, emitted by the U projectile moving at $v/c \approx 0.5$, show a clear dependence on the observation angle when being detected in the laboratory frame because of the Doppler shift. X rays from the Au target are emitted in the laboratory frame and show no Doppler shift. Right: Projected energy spectrum before (black) and after (blue) Doppler correction.

LYCCA for the case of the ^{80}Kr beam impinging on the beryllium target. The primary beam as well as different isotopes of various chemical elements can be distinguished. A resolution of $\Delta Z = 0.37$ for the charge and $\Delta A = 0.8$ for the masses could be obtained already. Finally, Coulomb excitation

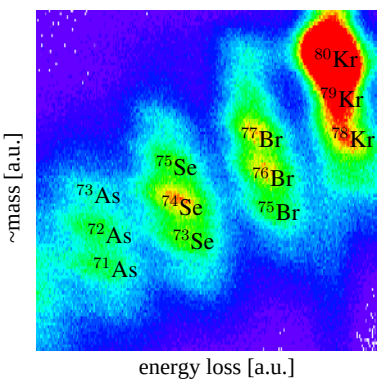

Figure 3. Identification of outgoing particles by LYCCA. This histogram is obtained by plotting ΔE, the energy loss in the Wall-DSSSD which is roughly proportional to an isotope's Z, against $A = T/(u\,c^2\,(\gamma - 1))$, as calculated from the time of flight and the kinetic energy deposition, T, in the Wall-CsI detectors. The masses are not correct on an absolute scale, and show a slight dependence on the energy-loss, which could be improved with an absolute energy and energy loss calibration. However, for the purpose of isotope selection, this is already sufficient. Isotope assignment was done after identifying ^{74}Se nuclides by means of a coincident γ spectrum. Together with the known primary beam, all other isotopes can be assigned by counting.

of the ^{80}Kr beam induced by the gold target was studied to demonstrate the performance of AGATA at relativistic beam energies and to optimize the pulse shape analysis and tracking conditions. ^{80}Kr was chosen because of its large $B(E2; 0_1^+ \rightarrow 2_1^+)$ value of 37.3 W.u. and the half-life of $T_{1/2} = 8.3$ ps of the first excited 2_1^+ state. The expected cross section for Coulomb excitation is $\sigma_{\rm clx} = 550$ mb. Fig. 4 shows the resulting spectrum after 8 hours of beam. The beam intensity was on average 35000 particles per spill, one spill being 10 s long. The total number of ^{80}Kr particles on target was $9.2 \cdot 10^7$.

4 Summary and Outlook to the Physics Campaign

The successful commissioning of the PreSPEC-AGATA setup at GSI showed a LYCCA mass resolution of $\Delta A/A \approx 1\%$ as well as a charge resolution of $\Delta Z/Z \approx 1\%$. The preliminary results for the

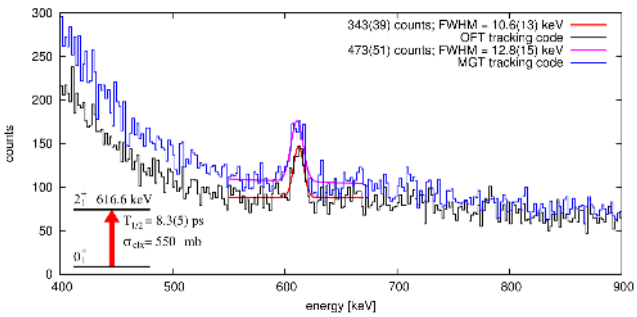

Figure 4. Spectra obtained for the decay of the $2^+ \rightarrow 0^+$ state in ^{80}Kr. Note that the efficiency as well as the energy resolution depends on the tracking algorithm used. The difference between MGT [9] and OFT [10] tracking is shown. The blue curve, corresponding to the MGT tracking, gives a total number of counts in the peak of 473(51) and a resolution of 2.2%. The black curve, obtained using the OFT tracking, has 343(39) counts in the peak and a resolution of 1.7%.

energy resolution of the AGATA array after Doppler correction is $\approx$ 1.7% at 616 keV and the efficiency with 14 crystals was estimated to be $\approx$ 0.8% . This is still below the expectations. Due to the complexity of the overall system, these values are likely to be improved because there is much room for optimization. In particular for data from the AGATA detectors, the results depend on complex software algorithms for PSA and γ-ray tracking that have to be further adapted and improved.

After commissioning, several experiments were conducted in 2012 as part of the first PreSPEC-AGATA physics campaign, using relativistic secondary beams of unstable neutron-rich nuclei or isomers produced either by target-induced fission of a relativistic uranium beam or in primary fragmentation reactions. These experiments combine the development of dedicated FAIR-relevant tools and techniques for high-resolution in-beam spectroscopy of relativistic radioactive ion beams with timely questions of nuclear structure research, such as Coulomb-excitation of a band-terminating isomer of ^{52}Fe, low-lying $E1$ modes of neutron-rich ^{64}Fe, evolution of the nuclear shapes of heavy Zr isotopes, or the collectivity of neutron-rich isotopes near ^{208}Pb.

5 Acknowledgments

Besides the funding agencies that supported the PreSPEC-AGATA set-up (see [3]) we thank in particular the Helmholtz International Center for FAIR for additional support for the research shown here. This work is supported by the European Community FP7 – Capacities ENSAR No. 262010.

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