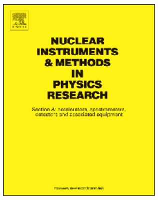
Nuclear Instruments and Methods in Physics Research A 806 (2016) 258–266

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima



Performance of the AGATA γ-ray spectrometer in the PreSPEC set-up at GSI

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For PreSPEC and AGATA Collaborations

ARTICLE INFO

Article history:
Received 29 July 2015
Received in revised form
2 October 2015
Accepted 9 October 2015
Available online 23 October 2015

Keywords:
AGATA
Gamma-ray spectroscopy
Gamma-ray tracking
Nuclear structure
Pulse shape analysis
HPGe detectors

ABSTRACT

In contemporary nuclear physics, the European Advanced GAmma Tracking Array (AGATA) represents a crucial detection system for cutting-edge nuclear structure studies. AGATA consists of highly segmented high-purity germanium crystals and uses the pulse-shape analysis technique to determine both the position and the energy of the γ-ray interaction points in the crystals. It is the tracking algorithms that deploy this information and enable insight into the sequence of interactions, providing information on the full or partial absorption of the γ ray. A series of dedicated performance measurements for an AGATA set-up comprising 21 crystals is described. This set-up was used within the recent PreSPEC–AGATA experimental campaign at the GSI Helmholtzzentrum für Schwerionenforschung. Using the radioactive sources ^{56}Co, ^{60}Co and ^{152}Eu, absolute and normalized efficiencies and the peak-to-total of the array were measured. These quantities are discussed using different data analysis procedures. The quality of the pulse-shape analysis and the tracking algorithm are evaluated. The agreement between the experimental data and the Geant4 simulations is also investigated.

1. Introduction

Numerous exciting nuclear-structure phenomena can be probed by in-beam γ-ray spectroscopy experiments. Innovative approaches in design of dedicated detection systems during the past decades led to significant advances in position sensitivity, photopeak efficiency and peak-to-total ratio (P/T) in γ-ray spectroscopy. Moreover, the most recent γ-ray spectrometers, such as AGATA [1] and GRETA [2], brought about the new concept of high-resolution germanium tracking arrays. This paper starts out with a retrospective overview of large γ-ray arrays (Section 2) in order to introduce the developments and requirements of the new tracking arrays.

Here, the focus is the performance of AGATA in the framework of the recent PreSPEC–AGATA campaign at the GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany [3,4]. Incoming particle identification is done event by event by Fragment Separator (FRS) detector systems [5]. Details of the AGATA subarray configured for the PreSPEC–AGATA campaign are presented in Section 3.

Using Monte Carlo simulations based on the Geant4 toolkit [6], extensive characterization studies of AGATA were performed [7,8].

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http://dx.doi.org/10.1016/j.nima.2015.10.032
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Nevertheless, it is important for the feasibility and the success of the present and future experiments to check experimentally the validity and reliability of this simulation tool, as well as the calculated performance figures. Therefore, a dedicated source measurement was performed and is described in detail in Section 4. Furthermore, the quantities such as photopeak efficiency, normalized efficiency as a function of the γ-ray energy and P/T were investigated following the procedure outlined in Section 5. The results of the analysis performed on the data alongside their interpretation and effect on other measurements are presented in Section 6. Moreover, these results were confronted to the output of the Geant4 simulation and their agreement is presented in Section 7.

Finally, the paper concludes with a short summary and an outlook for further investigations of performance of AGATA at GSI.

2. Concept of γ-ray detection with AGATA

The strength of AGATA is the ability to obtain positions and deposited energies of individual γ-ray interactions. Applying γ-ray tracking makes it possible to determine the sequence of the interactions.

The sophisticated design of AGATA came about only after a series of advancements of large γ-ray detector arrays [9,10]. At a very early stage of HPGe detectors' development, studies of nuclear structure could benefit from larger individual detectors, in comparison with Li-drifted Ge detectors. Further improvements focused on the increase of both the number of detectors and the solid angle covered by an array. This led to an enhancement of detection properties, mainly efficiency and energy resolution, and to some extent P/T. Additionally, a technique of background reduction was developed by means of Compton suppression. These efforts gave rise to the first arrays of HPGe detectors actively shielded by scintillating materials, which provided a substantial improvement of P/T.

Once a γ ray interacts with the detector medium, the energy recorded by those conventional arrays is the signal of any individual Ge-detector crystal. Typically, the absolute photopeak efficiency here depends on the intrinsic efficiency of the detector and its distance to the source. The P/T is determined by the intrinsic P/T of the individual detector elements, i.e. Ge detector plus surrounding Compton-suppression shield, and its geometry.

The next generation of Ge arrays relied on the novel idea of producing composite detectors, in particular the clover [11] and the cluster [12,13] detectors. Such detectors overcame the size limitation of the germanium crystals, while maintaining high granularity. This is important for the detection of long cascades of coincident γ rays. Arrays based on composite detectors increased efficiency over a large energy range and showed excellent P/T performance, thanks to the ‘add back’ concept [14], that uses signals from neighbouring Ge-detector crystals. Not only are the events originating in individual detectors summed to generate the total energy signal, but also the fraction of energies is recorded in cases of scattering between the crystals.

However, those detectors cover relatively large solid angles. This implies an uncertainty in γ-ray detection angle and quickly leads to Doppler-broadened peaks when studying γ-ray decays of fast-moving sources [15]. Secondly, it is difficult to distinguish two (or more) γ rays interacting at the same time in the same detector. This can lead to summing effects of coincident γ-ray transitions. The fact that those two γ rays are counted as one reduces the gain in efficiency and P/T provided by the advancement of composite detectors. Therefore, in the next generation of large γ-ray arrays the granularity was increased by means of additional contact segmentation [16,17].

The innovative concept of segmentation ensured smaller opening angles of the individual granuli, which allowed for shorter detector-to-source distance, without deteriorating energy resolution due to Doppler broadening. As a consequence, the efficiency improved significantly [8]. The first arrays had longitudinal segmentation and made the localization of the first interaction point in a two-dimensional plane possible [16,17]. In this generation of detector arrays it was not the opening angle of the crystal as a unity that affected the Doppler broadening, but that of an individual segment instead. The above mentioned summing effects are also significantly reduced. Finally, the P/T of such detector arrangements can be enhanced.

The most recent developments followed the line of segmentation introduced above, and the idea of γ-ray tracking was realized through the three-dimensional segmentation (longitudinal and azimuthal) of HPGe crystals of specific tapered shape. The prerequisite to tracking are the determined interaction points provided by the pulse-shape analysis (PSA). As a consequence, Compton-suppression shields can be excluded. This allows us to fill significantly more solid angle with Ge detectors. Currently two systems based on this principle are operational, one being in the U.S.A., GRETINA [2], and one in Europe, AGATA [1,18-20].

The present work provides the feedback on the application of PSA algorithms and helps to evaluate the reconstruction quality with respect to all three coordinates, x, y and z.

There are two types of algorithms dealing with the tracking of the subsequent interactions of a γ-ray in a Ge crystal. The first one, which is called back-tracking [21,22], is based on the reconstruction of the γ-ray path by starting the tracking procedure from the final interaction point. The second one is called forward-tracking [23–25] and starts by first recognizing clusters of interaction points. In this work, the forward-tracking algorithm is used and the results of the optimization are presented in Section 6.

3. AGATA detector configuration at GSI

In preparation for the HISPEC experiment at the FAIR-NuSTAR facility [26], the PreSPEC–AGATA campaign [3,4] was conducted at GSI in 2012 and 2014. Here, secondary radioactive beams are produced by fission or fragmentation of a primary stable beam delivered by GSI accelerator complex and selected by the FRS [5]. These beams are directed to a secondary target at relativistic energies of several hundred MeV/u. The in-flight emitted γ rays coming from the secondary reactions are therefore affected by a significant Doppler shift: the sources are moving with velocities of about 50% of the speed of light. The products of secondary nuclear reactions were discriminated using the Lund York Cologne CAlorimeter (LYCCA) [27].

The AGATA subarray composed of 21 encapsulated detectors was placed at its nominal distance of 23.5 cm to the centre of the secondary target. Such a configuration ensured optimal energy resolution of Doppler-corrected γ-ray spectra, alongside the improved efficiency of the array compared with the earlier RISING fast-beam set-up [15]. However, compared with the full AGATA array, this geometrical configuration results in only about 60% of the crystal surfaces in contact with neighbouring ones. Thus the probability of γ rays escaping the active Ge volume is rather large, which limits the tracking performance compared to a full 4π tracking array.

According to the original design [1], AGATA consists of triple clusters of Ge crystals (cf. Fig. 1). Hosting AGATA at the final focal plane of the FRS required a modified arrangement. Because of the rather large beam-spot size, the most inner ring of five triple clusters needed to be replaced. Newly developed double clusters were then put in place to guarantee angular coverage at forward angles. This is due to the Lorentz boost, which has to be considered in case of γ rays emitted from nuclei moving at relativistic energies.

The arrangement of AGATA detectors in doubles and triples is shown in Fig. 1. The triples are enclosed by blue lines and the doubles by green lines. Dashed lines refer to missing crystals in two triple clusters, as well as one crystal from an AGATA double.