Simulation studies on γ-ray tracking by germanium detectors

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In-beam γ-ray spectroscopy with radioactive isotope (RI) beams is instrumental in driving physics at RI beam facilities. A technical issue is that the Doppler-shift effect significantly modulates the laboratory energies of γ-rays emitted from fast RI beams in flight, nominally at $\beta = 0.5$–0.6 with the nominal energies of 150 to 250 MeV/nucleon in the RI Beam Factory (RIBF). The localization of γ-ray interaction points is thus crucial for detectors of in-beam γ-ray spectroscopy with RI beams to achieve precise Doppler-shift corrections and thus excel in γ-ray energy resolutions in the emitter's frame.

The γ-ray tracking technique of germanium detectors is a state-of-the-art method to achieve presently the best resolution for γ-ray energies in inverse kinematics. It has been implemented in the latest large-scale germanium clusters array GRETINA[1)] or AGATA. The RIBF hosted the HiCARI campaign[2)] in 2019 and 2020 to conduct the first studies with germanium detectors with the γ-ray tracking capability, which yielded successful outcomes. The "Gamma-ray Tracking in R5" (GT-5) project was launched in 2023 as a platform of tracking-type germanium detectors at the RIKEN Nishina Center to move associated experiments, data science, and instrumentations forward. A GRETINA quad module is planned to be procured within the framework of the Transformative Research Innovation Platform of RIKEN platforms (TRIP).[3)]

As the first step of the GT-5 project, a simulation study was conducted to evaluate tracking performances and investigate wider applications at the RIBF. The γ-ray tracking technique comprised of three steps: first the localization of γ-ray interaction points inside a germanium crystal, second the sequencing of localized interaction points in chronological order, third the reconstruction of γ-ray energies and incoming angles. The localization and sequencing are realized using a pulse shape analysis of multifold signals induced between the central contact and a set of segmented electrodes. The reconstruction algorithm relies on the two-body kinematics of Compton scattering of a γ-ray photon off an electron in a germanium crystal. The present study was focused on the performances related to the reconstruction part provided the localization is made with a precision of 2 mm FWHM and the sequencing is ideally handled.

The simulation calculations were performed by using the GEANT4 simulation library version 10.6 on the CentOS 7 Linux environment. The simulation data was analyzed by using the ROOT library version 6. We developed the reconstruction algorithm for multifold interactions equal to or more than three times, wherein the γ-ray energy and the incoming angle can both be determined. Based on the angle information, the γ-ray emission point can be localized on an event-by-event basis for RI beam experiments, where the emission point is also constrained by a one-dimensional axis of the beam path (Fig. 1). For 1 MeV γ-rays, the reconstructed energy resolution is evaluated to be approximately 200 keV FWHM. The position resolution of approximately 5 mm is obtained for the source localization when the detector is set 50 mm aside of the beam axis. By using this performance, it is possible to determine the γ-decay lifetime of RI beams excited by a fixed target, where the decay curve is translated into the spatial distribution of γ-ray emission points with respect to the target (Fig. 1).

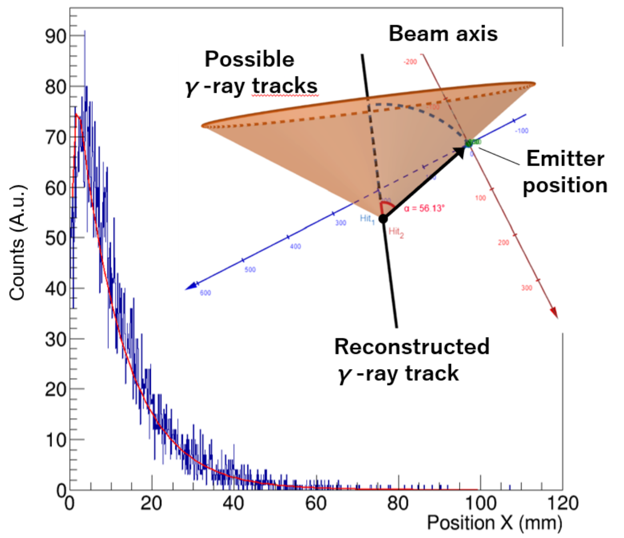

Fig. 1. Distribution of reconstructed γ-ray emission points with respect to the target for 1-MeV radiations from beams flying at $\beta = 0.6$. The γ-decay lifetime is set to 50 ps in this example. The schematic drawing shows how the emitter's position is determined from the crossing of the beam axis and the enveloppe of possible γ-ray tracks obtained from the tracking analysis.

The simulation results will be compared to the detector performances to be measured with the GRETINA quad module arriving in 2024.

References
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