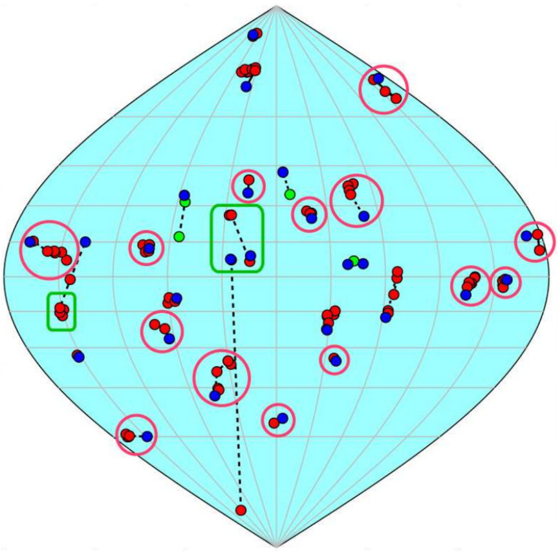
Developments and Implementation of γ-ray Tracking in AGATA: A review



Project report for FYST16 Modern Subatomic Physics

Author: Pim Nelissen

May 27, 2025

Contents

Abstract

Out of EUROBALL and GAMMASPHERE, the state of the art High-Purity Germanium detectors of the 20th century, came the development of The Advanced GAmma Tracking Array. AGATA is a European detector array which uses highly segmented HPGe crystals and the concept of γ-ray tracking to reconstruct the chain of Compton scattering events that γ-rays in nuclear structure studies can go through before fully depositing their remaining energy in a HPGe crystal through the photoelectric effect. This paper briefly discusses the conceptual background of gamma spectroscopy and its use cases, after which the experimental challenges with this type of spectroscopy are covered. The developments that led up to the construction of AGATA are discussed. Followed by this historic overview and motivation for γ-ray tracking, the computational procedure and algorithms involved with γ-ray tracking are discussed in detail. Performance of AGATA with these algorithms is discussed and compared with previous detector setups. On top of that, performance between the different procedures is assessed too. Recent developments in tracking, such as self-calibrating algorithms and graph neural networks, are briefly discussed and compared to existing methods.

1 Introduction

Gamma spectroscopy has broad-ranging use-cases in for example nuclear structure studies and medical imaging. Since gamma radiation is ionising, gamma spectroscopy is also of importance for non-proliferation, security and radiation source detection [1]. When it comes to nuclear structure, there is interest in studying the evolution of nuclear shell structure, the search for magic numbers, discovery of exotically shaped nuclei, and studying the phenomenon of shape coexistence. While γ-ray detection is easier than some other types of radiation [2, p. 237], there are many challenges. One relatively novel development, which today provides the highest sensitivity in gamma spectroscopy is the concept of γ-ray tracking. Tracking refers to algorithmically reconstructing the sequential Compton scatter events of an individual γ-ray. By finding the path that an individual γ-ray has traveled, the characteristics of its original emission from the nucleus decaying can be determined with greater accuracy.

The Advanced GAmma Tracking Array (AGATA) is a semiconductor γ-ray detector that has implemented such tracking. As such, AGATA achieves a higher detection efficiency than other High-Purity Germanium (HPGe) detector setups in the past. Developments in tracking detectors and algorithms have been instrumental for nuclear structure studies [3], because a major struggle for decades has been ensuring both a good signal-to-noise ratio while also having sufficient detector efficiency. AGATA addresses this by high segmentation (lots of physically separated elements, as well as segmentation within each detector element) in combination with tracking algorithms using the concept of pulse-shape analysis. The detector array is mobile and modular, and has thus seen use in various laboratories around Europe, and with various solid angle configurations possible as needed. This paper will give a brief review of not only AGATA, but also the developments prior to AGATA and the reasons why those developments were needed to push the field of nuclear structure studies forward.

2 γ-ray detection

Gamma spectroscopy is the field of study which attempts to determine the status and transitions of atomic nuclei through the corresponding absorption or emission of high energy photons. γ-rays are particularly suitable for probing nuclear structure due to their relative ease of detection [2, p. 237]. This, combined with the relatively high energy resolution, makes gamma spectroscopy an effective way to evaluate nuclear models. A metastable nucleus ${}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{X}^*$ may decay via γ-decay as follows

$${}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{X}^* \rightarrow {}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{X} + \gamma \ .$$

The energy loss due to recoil of the emitting nucleus ${}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{X}^*$ is usually negligible, meaning that the energy of the emitted photons is equal to the difference between nuclear states. This means a γ-ray spectrum serves as a 'fingerprint' for the nucleus.

Gamma spectroscopy can be done with both scintillator-based detectors as well as semiconductor (e.g. High-Purity Germanium, HPGe for short) detectors, where HPGe is preferred when a high energy resolution is required. The main challenge with using germanium-based detectors is the low efficiency.

3 Difficulties in γ-ray detection

The real challenge in successful gamma spectroscopy comes from accounting for the various interactions of γ-rays with matter (i.e. the detector). When it comes to photons emitted from decays, these are typically $< 1\,\text{MeV}$, where the photoelectric effect and Compton scattering dominate. But difficulties arise due to Compton scattering and other processes.

Compton scattering What makes measuring γ-rays through Compton interactions difficult is the incomplete absorption. γ-rays scatter off electrons in the detector crystals, and can also scatter several times before depositing their energy fully. The energy of the γ-ray after a Compton event is described by

$$E'_\gamma = \frac{E_\gamma}{1 + (E_\gamma/0.511\,\text{MeV})(1 - \cos\theta)}. \tag{1}$$

Due to the angle dependence, detections of these events can lead to a higher background continuum, complicating the identification of full depositions. Compton scattering is what γ-ray tracking addresses.

Pair production γ-rays with an energy of more than $1.022\,\text{MeV}$ are energetically allowed to create a positron-electron pair (which has $2 \cdot 511\,\text{keV}$ rest mass) upon interaction with matter as

$$(Z+)\gamma \to e^- + e^+.$$

This is the dominating interaction for high energy photons. However, the created positrons and electrons will eventually collide with other electrons and positrons, resulting in an annihilation

$$e^- + e^+ \to \gamma + \gamma\ ,$$

which produces two $511\,\text{keV}$ γ-rays. When it comes to gamma spectroscopy, the main problem is that these $511\,\text{keV}$ gammas can escape the detector, and thus leave deposits of energy that represent only a part of their original energy. This in combination with Compton scattering leads to additional counts in spectra which can complicate the identification of γ-ray peaks.

Doppler broadening In the pursuit of more exotic and energetic nuclei, experiments can involve faster moving nuclei. When a nucleus in motion relative to the lab frame releases a γ-ray, the energy measured can slightly vary depending on that velocity and its direction. This can lead to a broadening of the energy peaks, known as Doppler broadening.

4 Some progress

Compton scattering can be reduced by the use of anti-Compton shielding around the HPGe crystals (see Figure 1). The idea is that a γ-ray that scatters in the HPGe detector and escapes will be detected by the shielding. Pulses in the crystals which coincide with pulses in the shielding can then be rejected as it is certain that these are not full energy events. This increases the peak-to-total ratio (P/T) of the spectrum.

The last decades of the 20th century saw serious progress in addressing the other major issue, Doppler broadening. Examples of such projects are EUROBALL [5] in Europe, and GAMMASPHERE in the USA. The EUROBALL program, for example, saw an increase in efficiency while

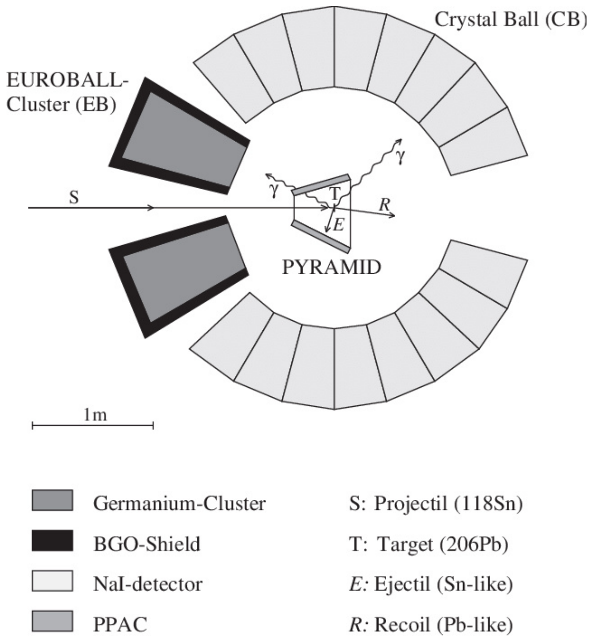


Figure 1: A schematic representation of EUROBALL clusters in an experimental setup. Reproduced from Ref. [4].

also reducing Doppler broadening by closely packing together HPGe crystals. This packing resulted in a higher efficiency than previous efforts, as well as better resolution [5]. For a 1.3 MeV γ-ray, detectors like EUROBALL and GAMMASPHERE can reach a peak efficiency of approximately 0.1 and a P/T ratio of about 0.6 [6]. The efficiency is limited primarily by scattered gamma rays escaping from the HPGe detector, with some loss due to reduced solid angle from the Compton shielding as well (see Figure 1). As early as the late 90s [6], it was concluded that, to combat these limitations, and thus further increasing efficiency, the number of detectors would have to be increased, as well as their packing density. When covering the entire solid angle, This would allow for combining signals from physically adjacent detectors as a way of recovering the full energy of the photon.

5 The Advanced GAmma Tracking Array

However, this would be very costly. Instead, the concept of highly segmented clusters was proposed, as visualised in Figure 2. With this kind of localisation, the interactions of individual γ-rays could be determined from position and energy information in neighbouring detector elements. This concept is what is referred to as 'tracking' and in the early 2000s lead to the proposal to build an Advanced GAmma Tracking Array, AGATA.

Unlike with charged particles, which can be tracked by the ionisation through a position sensitive detector, γ-ray tracking follow probabilistic laws and result in discrete interactions with the material. Reconstructing is thus not trivial, however it is not impossible. Gamma rays with energies between 150 keV and 10 MeV primarily interact through Compton scattering. From Equation 1 we can see that there is a clear relation between the energy of a gamma ray and

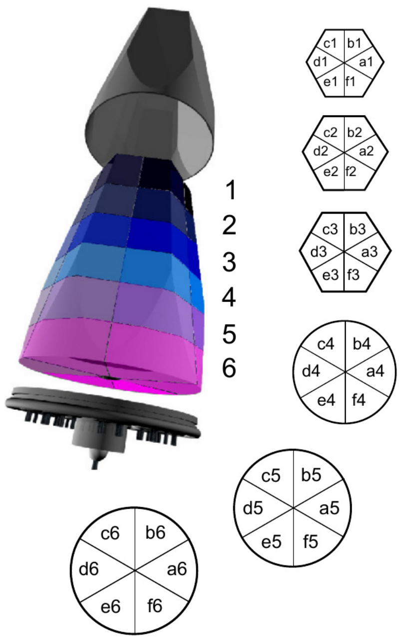


Figure 2: A visualisation of the segmentation of an AGATA detector element. There are 6 ring-like segments labeled $1-6$ in the longitudinal direction, where each segment is split into 6 more sectors labeled $a-f$. Figure reproduced from Ref. [3].

the scattering angle. However, we also have that deposited energy in the detector is just $E_e = E_\gamma - E'_\gamma$. As such, from the position and energy of a Compton event, we can determine the scattering that occurred and in this way track individual photons. In a laboratory setting the origin of the γ-ray is known, so energy and direction can be reconstructed one scattering event at a time [6].

Cluster geometry The HPGe detectors used in AGATA are divided into 6 longitudinal and 6 azimuthal segments, with a central electrode in the core, which measures the sum of all energies deposited in all the 36 segments. However, each segment can produce its own signal upon deposition of some energy. The power of AGATA comes in the arrangement of these detector elements. The basic unit of AGATA is a triple cluster of elements, which are closely packed to form a triangular shape. These units can then be assembled symmetrically on a spherical (or technically speaking a truncated icosahedron). Ultimately, this design can cover the full 4π solid angle [3], but can also be deployed in other configurations as needed.

6 AGATA tracking algorithms

Pulse shape analysis Pulse shape analysis (PSA) refers to the comparison between measured signals from Compton scattering and some kind of (simulated) signal based on a single interaction. Such an algorithm should be effective and efficient, that is, identify interaction points correctly [7], while also running for a relatively short time. The latter is important in γ-ray tracking due to the many interactions in each crystal. For each event, the measurements from the hit segment as well as neighbouring segment is given a Figure-of-Merit (FoM), essentially just a quantity

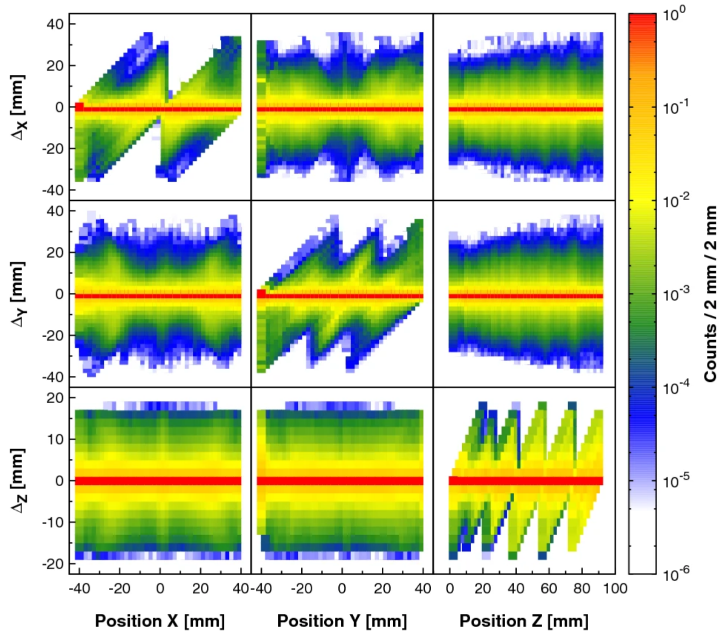


Figure 3: Position fluctuations as a function of PSA position based on experimental data, with counts normalised for comparison. The different patterns depend on the frame of reference and geometry of the detector. Figure reproduced from Ref. [8]

that uniquely represents the measurement, and thus, some γ-ray originating at some coordinate (x, y, z) with some deposited energy. The exact FoM used has varied over time but generally consists of some form of weighted sum [8] of the individual pulses. A visual example of the pulse signals in a segment is shown in Figure 5. This FoM is then compared to an existing database, either consisting of simulated data, experimental data, or some mixture of the two. Recent bootstrapping tests have been done to determine the position fluctuations of PSA based on experimental reference data, the results of which are shown in Figure 3. By analysis coincident pulses, then, all the interaction points of a single γ-ray can be found. Thus, PSA results in a list of interactions points $P_i(r_i, E_i)$, where r_i is the coordinate of the interaction and E_i the associated energy. Further computations are needed to determine the γ-ray origin and energy, and for this purpose there are two types of algorithm; back-tracking and forward-tracking algorithms.

Forward-tracking The first step is typically to project the interaction points P_i onto a spherical coordinate system, see Figure 4. Let

$$\theta = acos(\frac{\vec{r}_i \cdot \vec{r}_j}{|\vec{r}_i||\vec{r}_j|})$$

be the relative angular distance between two interaction points P_i, P_j with respect to the origin of the system. Then, if $\theta \leq \alpha$ for some α, the point P_j is assigned to the cluster that P_i belongs to. Otherwise, if $\theta > \alpha$ for all interaction points in the event, a new cluster is created for P_j. By simulated data [10], it was found that

$$\alpha_{\max} \propto 1/N^{0.9} \ ,$$

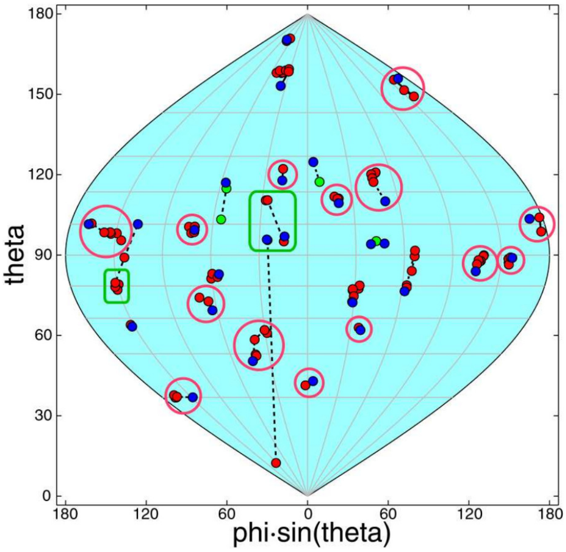


Figure 4: Forward-tracking based reconstruction of γ-rays, from $E_\gamma = 1\,\mathrm{MeV}$, $M_\gamma = 30$ event. Red dots represent Compton scattering events, blue dots represent full deposition. Correctly reconstructed gamma clusters are circled in red, unsuccessful ones in green. Figure reproduced from Ref. [9]

where N is the number of interaction points in the event. From this it can be seen that the clustering will be stricter with more interactions, and looser with less of them. Now, by assuming that a chain of Compton interactions happens withing some cluster restricted by α_{max}, the interaction points P_i are clustered and considered candidate interactions for one γ-ray. By minimizing another FoM [10] based on interaction probabilities and the Compton scattering formula (Equation 1), the correct order of points P_i is found. For a visual representation of the clustering, refer to Figure 4.

Back-tracking The back-tracking algorithm is in reverse order but otherwise quite similar to the forward-tracking algorithm. First is finding a candidate for a final interaction point P_{N}. The photoelectric absorption is typically on the order of 100 to 250 keV, so deposited energy in this range signifies a potential candidate. Once a candidate is found, the goal is to find a point $P_{\mathrm{N}-1}$ which satisfies the same energetic constraints as in the forward tracking, so once again the scatter angle and energies are consistent with Equation 1. If such a point $P_{\mathrm{N}-1}$ is found, the search for $P_{\mathrm{N}-2}$ begins in a similar fashion. Both of these algorithms use the same physics (Compton and photoelectric effect) in order to track γ-rays. Once a set of N points P_i is identified and determined to correspond to one γ-ray, based on pulse-shape analysis and either forward or backward tracking, these points are removed from the pool of interactions of an event, and the procedure is repeated until, hopefully, all measured interactions have been successfully attributed.

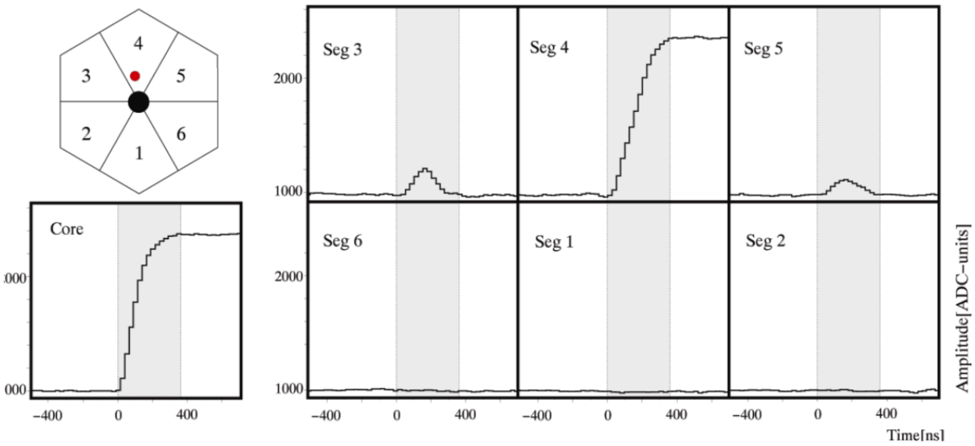


Figure 5: An example of the signal from a full energy deposition in an HPGe cluster as used in AGATA. The full energy is deposited in segment 4 with traces visible in neighbouring segments. Figure reproduced from Ref. [9].

7 Performance of AGATA

Between ≈ 100 keV and 5 MeV, Compton scattering is the dominant interaction for γ-rays. From studies at GSI and GANIL [11, 12], the measured efficiency for γ-ray tracking at 1.4 MeV was 2.50(2)% and 3.67(1)% respectively [10], with a P/T ratio of 38(1)% and 36(1)%. An efficiency plot for this regime, based on measurements from Lalovic et al. [12] is shown in Figure 6.

Backtracking vs forward tracking The first comprehensive comparison between backtracking and forward tracking was done by Lopez-Martens et al. [13]. By using Monte Carlo simulated data for a 4π Ge shell, performance was compared between the two types of tracking. Figure 7 shows that overall performance of forward tracking is slightly better. However, the back-tracking algorithm reconstructs different events than the forward-tracking algorithm, especially for high multiplicity (many interactions in one event). Thus, a combination of both can actually give even better tracking performance.

8 New algorithms and methods

Recent developments [14, 15] in tracking algorithms show further progress in improving performance of AGATA.

ExpTrack One such suggested algorithm is the self-calibrating algorithm called ExpTrack [14]. The idea is to combine probability densities for Compton scatter events by deposited energy and scattering angles from experimental data. At each step in the tracking, only the scattering angles with the highest probability are accepted. It is referred to as self-replicating because of this feature; there is no imposed limit α_{max} like with forward tracking, but the selection is simply based on the 'most likely' next interaction point. The advantages are that this directly accounts for detector uncertainties, and it has been shown to slightly outperform forward tracking for a $N = 2$ chain of interactions belonging to a 661.7 keV γ-ray, about 96.3% reconstruction success

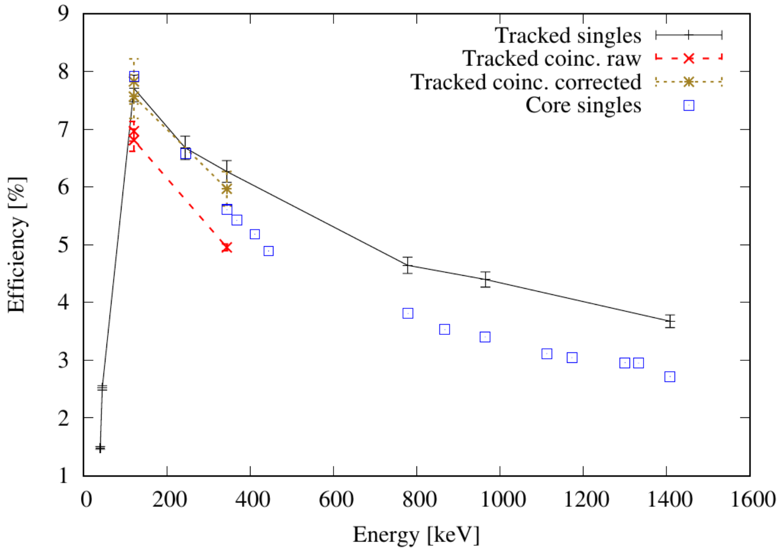


Figure 6: Performance of AGATA in the medium γ energy range at the GANIL facility. A forward tracking algorithm was used. Figure adapted from Ref. [11].

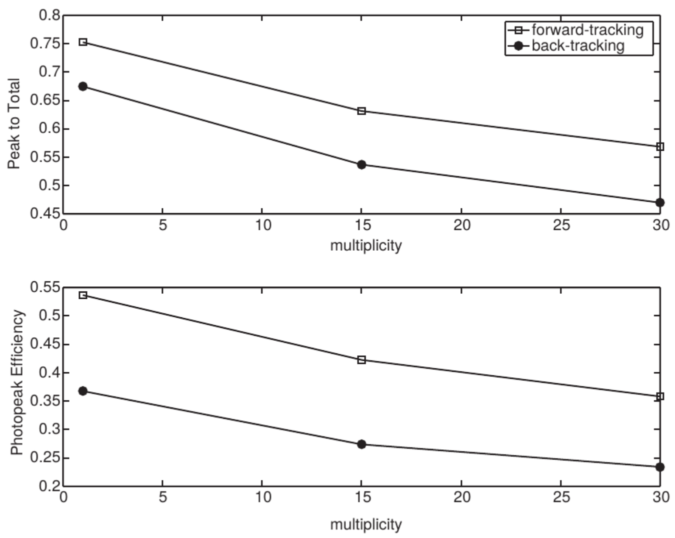


Figure 7: Comparison of forward tracking and back-tracking performance in terms of P/T ratio and photopeak efficiency, which is just how effectively the detector can register the full energy. The figure shows that forward-tracking generally performs better than back tracking, although both are commonly used in order to crosscheck results. Ref. [13].

versus 92.1% for forward tracking. The main problem is that it was only tested for this specific case.

Graph neural networks Another approach has been the use of graph neural networks, a type of machine learning algorithm based on graph theory, where *nodes* represent features of the data, which are connected by relationships called *edges*. The GNN passes information between nodes along the edges iteratively in order to learn. One advantage is that machine learning algorithms are, by default, physics agnostic; there is no 'external knowledge' added. Along with the fact that γ-ray interactions naturally are graph-like - that is, there are points (nodes) connected by scattering paths (edges) - this seems like a logical step. Andersson et al. [15] describe a GNN where the nodes represent interaction points $P_i(r_i, E_i)$ and the weights ω of edges between two points P_i, P_j represent likelihoods of the two points belonging to the same γ. This GNN slightly outperforms in terms of P/T ratio, especially for higher multiplicity. Where the GNN P/T ratio remains relatively equal across the range of multiplicity tested, the traditional forward tracking and back tracking algorithms are significantly worse with more interaction points per event (see once again Figure 7).

9 Conclusion

The past 20 years have seen significant development in the space of γ-ray tracking. From EUROBALL to AGATA with forward tracking, we observed a significant improvement in efficiency and a notable improvement in P/T ratio, but there is room for further improvement. Recent studies using probability based calibration algorithms and neural networks show promising results, but more research needs to be done in order to make progress and further improve the spectroscopic results. Nonetheless, AGATA remains the state of the art γ-tracking detector array with relevancy to today's nuclear structure studies as well as into the future.

References

[1] Kai Vetter et al. "Gamma-Ray Imaging for Nuclear Security and Safety: Towards 3-D Gamma-Ray Vision". In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 878 (Jan. 2018), pp. 159–168. ISSN: 01689002. DOI: 10.1016/j.nima.2017.08.040.

[2] Krane. *Introductory Nuclear Physics*. Wiley, 1987.

[3] S. Akkoyun et al. "AGATA—Advanced GAmma Tracking Array". In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 668 (Mar. 2012), pp. 26–58. ISSN: 01689002. DOI: 10.1016/j.nima.2011.11.081.

[4] I. Peter et al. "Enhanced Neutron Pair Transfer and Collective Excitations in the System 206Pb + 118Sn at Barrier Energies". In: *Eur Phys J A* 16.4 (Apr. 2003), pp. 509–525. ISSN: 1434-6001, 1434-601X. DOI: 10.1140/epja/i2002-10124-7.

[5] C. Rossi Alvarez. "The EUROBALL Array". In: *Il Nuovo Cimento A (1971-1996)* 111.6–7 (June 1998), pp. 601–606. ISSN: 1826-9869. DOI: 10.1007/BF03185326.

[6] I.Y. Lee. "Gamma-Ray Tracking Detectors". In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 422.1–3 (Feb. 1999), pp. 195–200. ISSN: 01689002. DOI: 10.1016/S0168-9002(98)01093-6.

[7] R. Venturelli and D. Bazzacco. *Adaptive Grid Search as Pulse Shape Analysis Algorithm for Gamma-Tracking and Results.* LNL Annual Report, 2004.

[8] AGATA and OASIS collaborations et al. "Position Uncertainties of AGATA Pulse-Shape Analysis Estimated via the Bootstrapping Method". In: *Eur. Phys. J. A* 57.2 (Feb. 2021), p. 64. ISSN: 1434-6001, 1434-601X. DOI: 10.1140/epja/s10050-021-00385-z.

[9] D. Bazzacco et al. *AGATA, Technical Proposal for an Advanced Gamma Tracking Array for the European Gamma Spectroscopy Community.* Ed. by J. Gerl and W. Korten. AGATA collaboration, 1991, p. 87.

[10] F. C. L. Crespi et al. "AGATA: Performance of $$\gamma $$-Ray Tracking and Associated Algorithms". In: *Eur. Phys. J. A* 59.5 (May 22, 2023), p. 111. ISSN: 1434-601X. DOI: 10.1140/epja/s10050-023-01019-2.

[11] J. Ljungvall et al. "Performance of the Advanced GAmma Tracking Array at GANIL". In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 955 (Mar. 2020), p. 163297. ISSN: 01689002. DOI: 10.1016/j.nima.2019.163297.

[12] N. Lalović et al. "Performance of the AGATA Gamma-Ray Spectrometer in the PreSPEC Set-up at GSI". In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 806 (Jan. 2016), pp. 258–266. ISSN: 01689002. DOI: 10.1016/j.nima.2015.10.032.

[13] A. Lopez-Martens et al. "Gamma-Ray Tracking Algorithms: A Comparison". In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 533.3 (Nov. 2004), pp. 454–466. ISSN: 01689002. DOI: 10.1016/j.nima.2004.06.154.

[14] P. Napiralla et al. "Approach to a Self-Calibrating Experimental Gamma-Ray Tracking Algorithm". In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 955 (Mar. 2020), p. 163337. ISSN: 01689002. DOI: 10.1016/j.nima.2019.163337.

[15] Mikael Andersson and Torbjörn Bäck. "Gamma-Ray Track Reconstruction Using Graph Neural Networks". In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 1048 (Mar. 2023), p. 168000. ISSN: 01689002. DOI: 10.1016/j.nima.2022.168000.