



HAL
open science

On the AGATA performances at low γ -ray energies

E Clément, J Ljungvall, R M Pérez-Vidal, J Dudouet, L Ménager

► **To cite this version:**

E Clément, J Ljungvall, R M Pérez-Vidal, J Dudouet, L Ménager. On the AGATA performances at low γ -ray energies. 2022. in2p3-04035178

HAL Id: in2p3-04035178

<https://in2p3.hal.science/in2p3-04035178v1>

Preprint submitted on 17 Mar 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons CC0 - Public Domain Dedication 4.0 International License

On the AGATA performances at low γ -ray energies

E. Clément^a J. Ljungvall^b R. M. Pérez-Vidal^c J. Dudouet^d
L. Ménager^a

^a*Grand Accélérateur National d'Ions Lourds (GANIL), CEA/DRF-CNRS/IN2P3,
F-14076 Caen Cedex 05, France*

^b*Laboratoire de Physique des 2 infinis Irène Joliot-Curie, CNRS / Université
Paris-Saclay / Université de Paris 91405 Orsay cedex, France*

^c*INFN Laboratori Nazionali di Legnaro, IT-35020 Legnaro, Italy*

^d*Université Lyon, CNRS/IN2P3, IP2I-Lyon, F-69622, Villeurbanne, France*

Abstract

The response function of the Advanced GAMMA Tracking Array (AGATA) at low energy has been evaluated with γ -ray sources from 20 keV to 1.4 MeV. Particular interest was given to the treatment of γ -ray below 100 keV which interact predominantly by photo-electric effect in the first centimeter of the germanium crystal. The performances are evaluated and improvements to the data processing are proposed.

Key words: AGATA spectrometer, γ -ray tracking, Pulse Shape Analysis

1 Introduction

High-resolution γ -ray spectroscopy plays a major role in nuclear structure, nuclear astrophysics and nuclear reaction mechanism studies. Continuous progress in detector technology and data analysis lead to improved sensitivity giving access to more exotic nuclei and detailed nuclear spectroscopic information. In recent years, dedicated set-ups coupling large high-purity Ge arrays and ancillary detectors, such as magnetic spectrometers or separators, scintillators for high energy γ -ray detection or fast-timing measurements, and particle detectors, have been developed in large scale heavy-ions facilities. Thanks to these improvements, high resolution γ -ray spectroscopy of exotic nuclei was performed with unprecedented sensitivity from light to heavy nuclei and from the proton to the neutron drip-lines [1]. In the quest of the study of heavy elements, new reaction mechanisms are proposed using heavy ions collisions

31 above the Coulomb barrier [2–4]. In order to perform their prompt γ -ray spec-
32 troscopy, high performance magnetic spectrometers are required to identified
33 the produced isotopes. In spite of their high performances, the unique element
34 identification is not possible due to the low energy of the produced recoil
35 and it is proposed to use the atomic x-rays emitted at the target position, to
36 identify the element number. In this particular framework, the performances
37 of AGATA [5] and the response function of the Pulse Shape Analysis and
38 Tracking algorithms for photons below 100 keV are investigated in the present
39 manuscript.

40

41 **2 Source measurements**

42 The AGATA response function was measured from 24.0 keV to 1.4 MeV with
43 a particular focus on γ -rays energies below 100 keV using radioactive sources
44 of ^{113}Sn ($T_{1/2}= 115$ days), ^{141}Ce ($T_{1/2}= 32.5$ days), ^{152}Eu ($T_{1/2}= 13.33$ years)
45 and ^{203}Hg ($T_{1/2}= 46.59$ days) placed at the center of the array (see table 1).
46 Individual crystal counting rate was kept between 100 and 500 Hz. A 15 keV
47 electronic threshold was reached in the measurement. The data processing fol-
48 lows the usual AGATA procedure and Pulse Shape Analysis is performed on
49 an event-by-event basis using the Adaptive Grid Search and the ADL libraries
50 [5]. The individual crystal event are merged in software using a coincidence
51 windows of 500 ns based on the GTS timestamp distribution. The OFT track-
52 ing algorithm is used with standard parameters [6]. Below 100 keV, several
53 difficulties impact on the treatment a such interactions for γ tracking arrays.
54 Indeed, the γ -rays absorption will mainly process by a single interaction in a
55 photoelectric event at the very front of the AGATA crystal [5] where electric
56 fields are the less coaxial due to the crystal shape, and with very low signal
57 amplitude suffering from electronic noise which can impact the quality of the
58 Pulse Shape Analysis [7].

59 **3 Results**

60 A schematic figure of an AGATA crystal is shown in figure 1. More details can
61 be found in [8]. The (X,Y) coordinates define the slices with index "1" of the
62 6 front segments facing the radioactive sources. The Z coordinate corresponds
63 to the depth in the cristal, the last slice of segment being number "6".

64 The results of the measurements are shown in figure 2. The top figure is
65 shown in logarithmic scale in energy to highlight from the low energy part to
66 the high energies regime. The bottom figure is in linear scale and zoomed on

Table 1
X-rays measured in the present work

Source	Energy [keV]	Intensity
^{152}Eu	39.52	21.0 %
	40.118	37.7 %
	45.293	3.75 %
	45.414	7.26 %
	46.578	2.40 %
^{141}Ce	35.55	4.90 %
	36.026	8.85 %
	40.748	1.67 %
^{203}Hg	70.83	3.69 %
	72.873	6.19 %
	82.574	1.43 %
^{113}Sn	24.00 + 24.21	28.0% + 51.8%
	27.23 + 27.27 + 27.86	4.66% + 9% + 2.39%

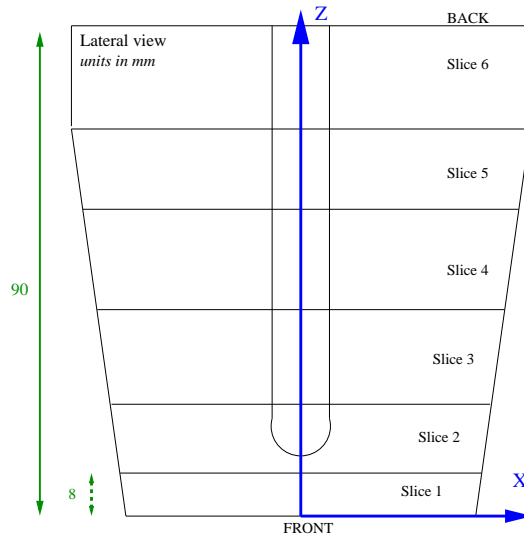


Fig. 1. (Color online) The schematic lateral view of an AGATA crystal. The figure shows the numbering of the slice from 1 (front, facing the source) to 6 (back). The first slice has a reduced size of 8 mm. More details in [8]

67 the x-ray region. The different experimental points show the relative efficiency
 68 obtained using different data processing, as described in the following section,
 69 and normalised to the γ -ray intensity measured in the core signal.

70 3.1 Segment procedure

71 The black points represent the normalized intensities measured in the electric
72 segment, i.e. from individual hits before the tracking filter. Below 100 keV,
73 the ratio is close to 1 since the interaction occurs with a single photoelec-
74 tric process within a single electric segment. Beyond this turning point, the
75 contribution of the Compton scattering between individual segment increases
76 leading to a relative efficiency which decreases until $\simeq 1$ MeV and saturates
77 at $\simeq 0.20$ indicating 20% of "single" interaction in a segment. Multiple inter-
78 actions in a given segment are not separated in the present process.

79 3.2 Add-back procedure

80 The red squares shows the relative efficiency after an Add-back procedure
81 of the neighbouring core output [9]. Below 200 keV, the incident photons is
82 absorbed in the large volume of the HPGe crystal and the relative efficiency is
83 close to 1. Beyond, Compton scattering between crystal occurs and an Add-
84 back factor of 1.35 is reached at the 1.4 MeV ^{152}Eu line. One can noticed that
85 the procedure induces a loss of intensity below 40 keV. One can speculate that
86 a single interaction in a given crystal is added to noise from a neighbouring
87 crystal. The loss is about 20% at 25 keV.

88 3.3 Tracking procedure

89 The green triangles shows the relative efficiency after OFT tracking. Above
90 80 keV, the OFT tracking performs as well as the core Add-back procedure
91 with a better Peak-To-Total ratio in particular below 500 keV. Below 80 keV,
92 in the x-rays area, a continues drop of the relative efficiency is observed. Such
93 decrease is not reproduced in the OFT simulation using the interaction point
94 from the GEANT4 simulation [10] and the same tracking parameters. For 40
95 keV γ -ray energy, GEANT4+OFT with the default packing of the simulated
96 hits gives 60% of photopeak-efficiency with respect to the core output but
97 measured at the level of 40%. This is attributed to Pulse Shape Analysis
98 default in this energy regime. The AGATA processing allows a smearing of
99 the hits positions determined by the Pulse Shape Analysis within the voxel.
100 This has no effect on the efficiency as shown by the dark blue triangles.

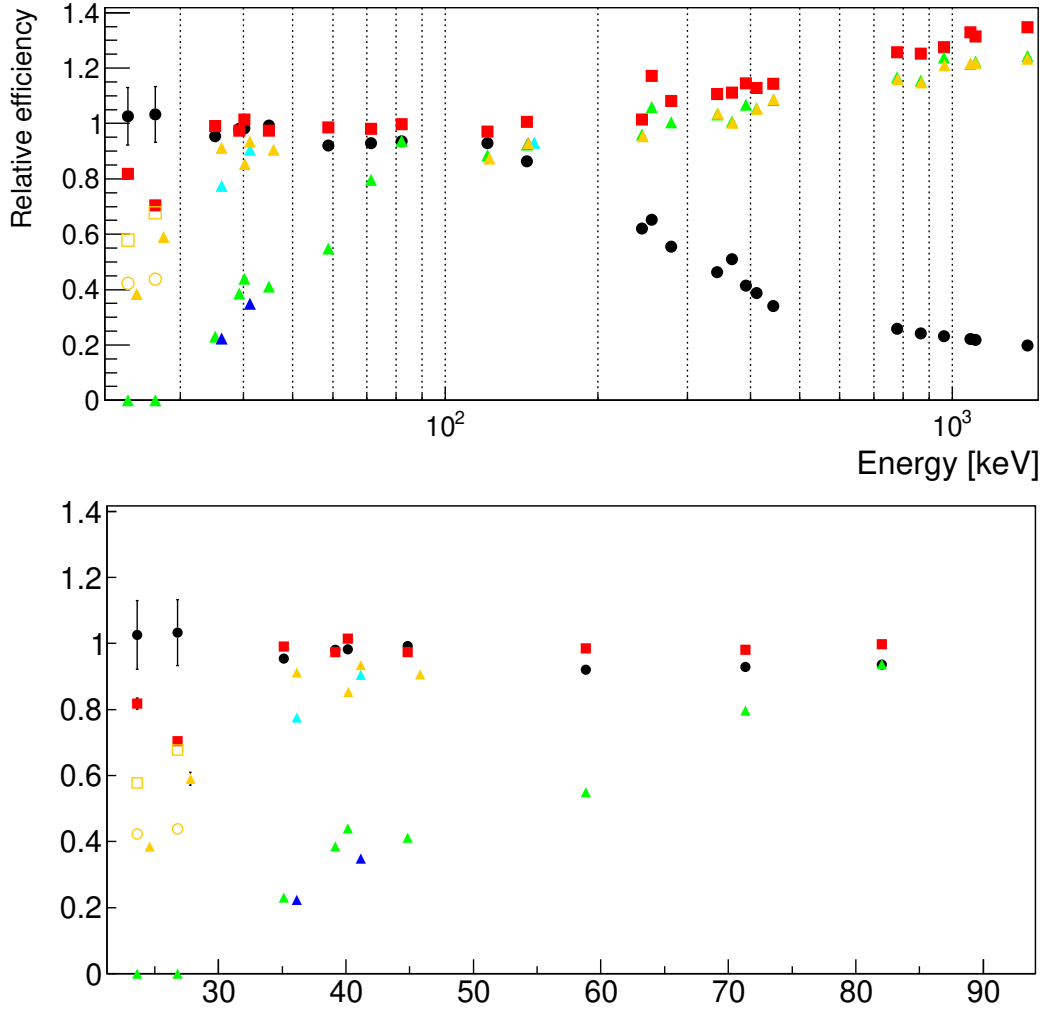


Fig. 2. (Color online) Relative efficiencies measurement as a function of the γ -ray energy (see text). Black : Segment energy. Red : Core Add-back. Green : Tracked. Dark blue : Tracked with smearing. Cyan triangle : 1mm correction. Orange triangle : 500 μm correction. Orange open squares : 100 μm correction. Orange open circle 10 μm correction.

101 3.4 Analysis of the non-tracked events

102 In this section, the photopeaks events rejected by the tracking algorithm are
 103 identified and analyzed. In the figure 3, the experimental hits distribution,
 104 computed by the Pulse Shape Analysis, as a function of the depth in the crystal
 105 (Z), gated on the ^{141}Ce x-rays is shown. The experimental distribution shows a
 106 flat pattern, randomly distributed between the entrance of the crystal and the
 107 end of the first slice at 10 mm. A distribution appears also at the back of the
 108 crystal (from 70 mm) and is attributed to either high energy photons entering
 109 by the crystal face and back-scattering in the cryostat, front-end electronic
 110 and LN2 dewar; or low energy photons from the room background entering

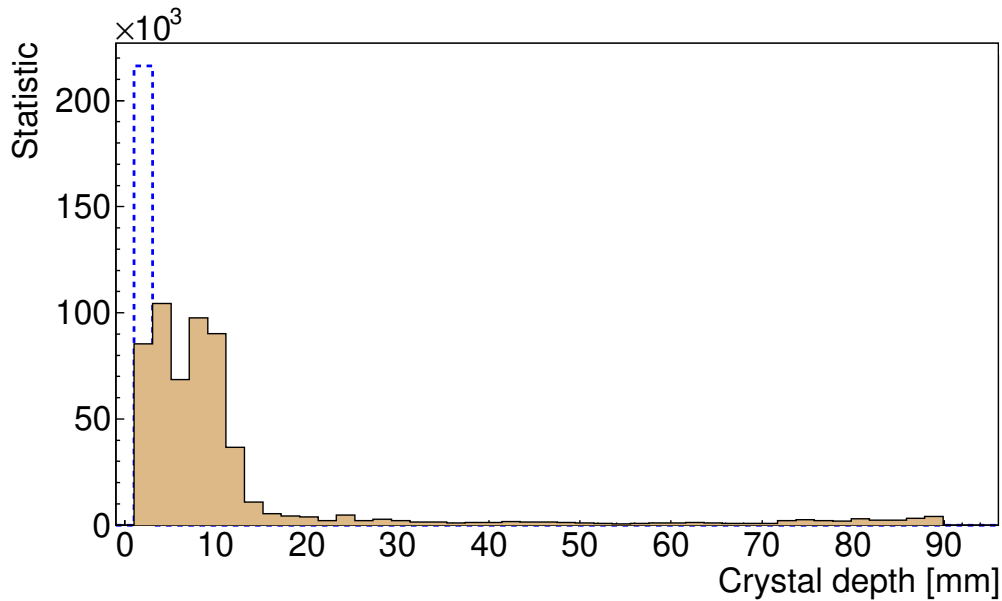


Fig. 3. (Color online) Experimental hits distribution as a function of the depth in the crystal gated on the ^{141}Ce x-rays. In blue, hits accepted by the tracking algorithms. In the filled histogram, rejected hits by the algorithm.

111 by the back of the crystal. The measured flat distribution below 15 mm is non
 112 physical since such low energy γ -ray must be absorbed within the first mm.
 113 The filled distribution shows the rejected hits by the tracking algorithm. The
 114 blue histogram shows the tracked events, which means hits accepted by the
 115 OFT algorithm and located by the Pulse Shape Analysis in the first millimeter
 116 of the crystal. OFT is identifying these events as a single photo-electric event
 117 which could only occur within the first two millimeters. One can also notice
 118 that the low energy events placed at the back of the crystal are well rejected
 119 by the OFT tracking algorithm.

120 The figure 4 shows the corresponding GEANT4 simulation for the ^{141}Ce x-
 121 rays energy. The distribution is well centered on the first millimeter as expected
 122 and disagrees with the experimental distribution. This disagreement leads to
 123 a high rejection of the hits by the OFT algorithm.

124 The spatial distribution of accepted and rejected hits is further analyzed.
 125 The (X,Y) distributions in the first front slice (segment 1 in figure 1) of the
 126 corresponding events are shown in figure 5. Figure a (b) shows the accepted
 127 (rejected) hits by the OFT tracking. The Z scale is identical. The distribution
 128 of the rejected hits is rather uniform as the accepted hits distributions shows a
 129 deficit in the middle of the crystal surface. The hit distributions are converted
 130 into radius coordinate (from central contact to crystal side) as a function of Z
 131 in figure 6. The radius is determined for the accepted (rejected) in blue (filled)
 132 interactions showing a specific pattern highlighting the large radius.

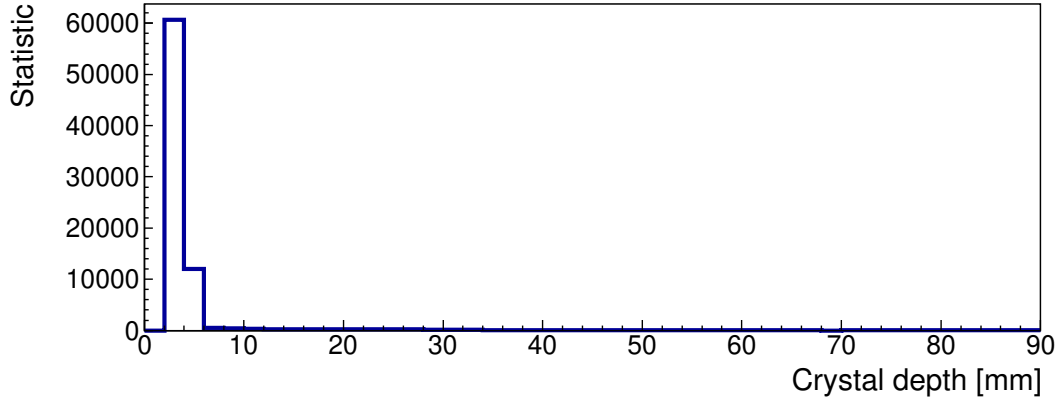


Fig. 4. (Color online) Simulated hits distribution as a function of the depth in the crystal gated on the ^{141}Ce x-rays.

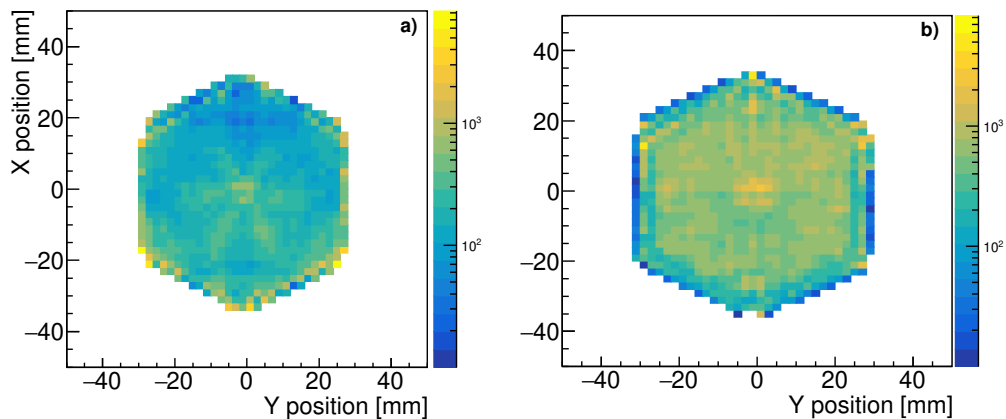


Fig. 5. (Color online) Two dimensional hits distribution for the front slice gated on the ^{141}Ce x-rays. (a) Accepted hits. (b) Rejected hits.

133 This significant pattern reflects the specificities of the low energy signals. We
 134 refer in the following to two other studies which have investigated the low
 135 energy signal in AGATA. Experimentally, the low energy response function
 136 of highly segmented AGATA-type crystal was scanned at the IPHC scanning
 137 table [7]. The analysis of the 122 keV transition from ^{152}Eu reveals specific
 138 features. First it is demonstrated that, by opposition to energies greater than
 139 200 keV, the database used presents overall large inconsistencies with the
 140 collected data. Also, already at 122 keV, the core and segment contacts have
 141 ~ 5 keV and ~ 2 keV noise on their maximum amplitude [7]. Much larger
 142 values can be extrapolated below 50 keV inducing, first, a large bias on the
 143 χ^2 method for the Pulse Shape Analysis and, secondly, impacting the time
 144 resolution and time alignment with respect to the reference database. Another
 145 very interesting observation is made in the scanned data. For such low energy
 146 signal, the transient signals amplitudes are small with respect to the net charge
 147 signal. At 122 keV, the transient signals are generally ~ 15 -10% except for
 148 the segment border where the segment signal is collected, it means at large
 149 radius, where they may rise up to $\sim 30\%$ [7]. This larger amplitude lead to

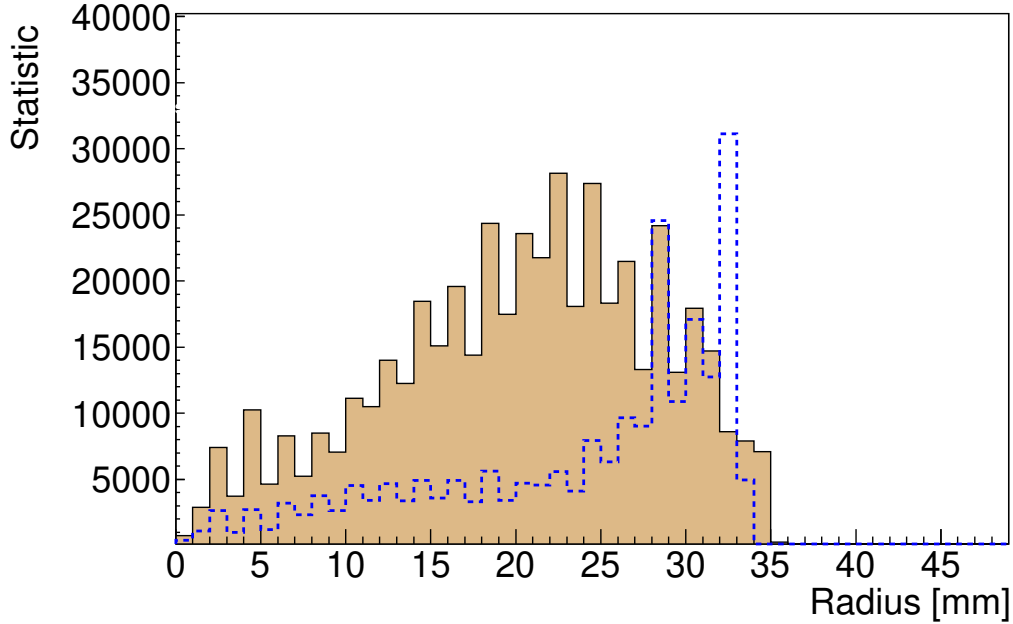


Fig. 6. (Color online) Distance to the central contact in the front slice gated on the on the ^{141}Ce x-rays for the front slice. In blue, hits accepted by the tracking algorithms. In the filled histogram, rejected hits by the algorithm.

150 higher signal-to-noise and better time resolution since it occurs closer to the
 151 signal collection. Therefore one can speculate that the Pulse Shape Analysis
 152 performs better leading to a better estimation of the Z coordinate and finally
 153 a higher acceptance rate by the OFT tracking as observed in figure 6.

154 Complementary to the general trend toward the side of the crystal, "hot spots"
 155 can identified in the corner of the crystal (beyond 32-33 mm) in figure 6. They
 156 were investigated by mean of simulation this time and these "hot spots" are
 157 most likely related to an incorrect determination of the start time for these
 158 events further enhanced by the low amplitude and noisy signal induced by the
 159 low energy γ -rays [11].

160 As a result, we support that the low efficiency observed at low energies in
 161 AGATA is due to a random estimation of the Z position by the PSA and not
 162 from the tracking algorithm.

163 The random character of the PSA results and its impact on the tracking is
 164 evaluated using the ADL bases directly. The grid positions in the first ring
 165 of the ADL basis for A002 are randomly extracted and processed in OFT for
 166 a 36 keV γ -ray. In the following, method 1 refers to the choice of random
 167 (X,Y,Z) positions and method 2 refers to a random distribution of Z into a
 168 (X,Y) column which mimic an accurate radius determination. The result of
 169 the corresponding Z distributions are shown in figure 8. The distribution is in
 170 agreement with the distribution of rejected event shown in figure 3.

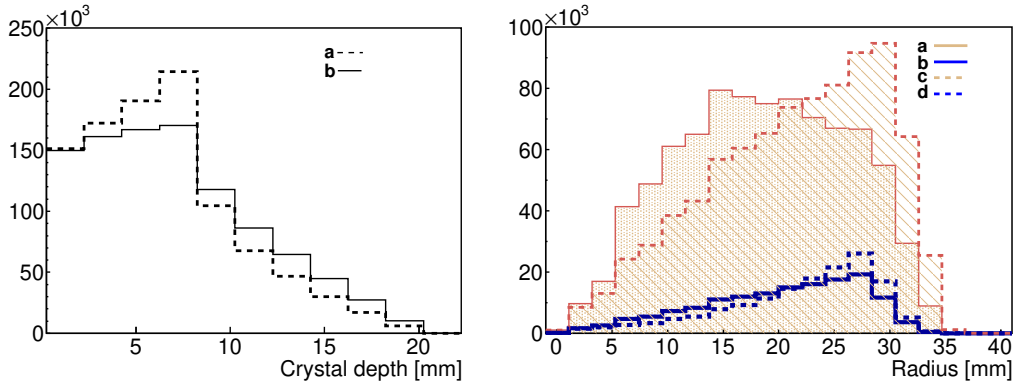


Fig. 7. (Color online) Left : Z distribution for random points in the first ring of an asymmetric A-Capsule ADL bases. a, is for equal weights for each points (method 1) and b, is for equal weight for all (x,y) pairs (method 2). Right: Radial distribution for accepted (b,d) and rejected (a,c) events for random choices method 1 (a,b) and 2 (c,d)

171 The radial distribution is computed for accepted and rejected event using
 172 both method for the initial position. The distributions are shown in the figure.
 173 The agreement with figure 6 is reasonable with same trends. Similarly to the
 174 measurement, the accepted hits are more centered around large radius at 30
 175 mm as the rejected hit distribution is centered at mid-radius and flat. The
 176 comparison between method 1 and 2 for the rejected hits seems to show that
 177 all coordinates are randomly determined and the measured distributions reflect
 178 only the grid granularity of the ADL bases convokuated with the shape of the
 179 crystal.

180 4 Post- Pulse Shape Analysis corrections

181 Post- Pulse Shape Analysis corrections are proposed before running the track-
 182 ing algorithm to improve the efficiency at low energy. Before tracking, crystal
 183 events with a segment multiplicity equal one, an energy below 100 keV and
 184 located below 10 mm are selected. An arbitrary depth position is forced. We
 185 scanned different values to optimize the OFT efficiency. In figure 2, the posi-
 186 tion is forced to 1 mm (cyan triangle) and 0.5 mm (orange triangle). The 1
 187 mm position allows to recover more than 90% efficiency as low as 40 keV as
 188 the 0.5 mm position allows to recover until 30 keV without impact at all the
 189 higher energies. An efficiency of 60-70% can be reached for the ^{113}Sn x-ray
 190 by adjusting the depth to 100 μm (orange squares). However, an even more
 191 shorter depth (10 μm orange circle) leads to a significant reduction of the gain
 192 reached with the 100 μm position showing that below 30 keV more advanced
 193 solutions are needed.

194

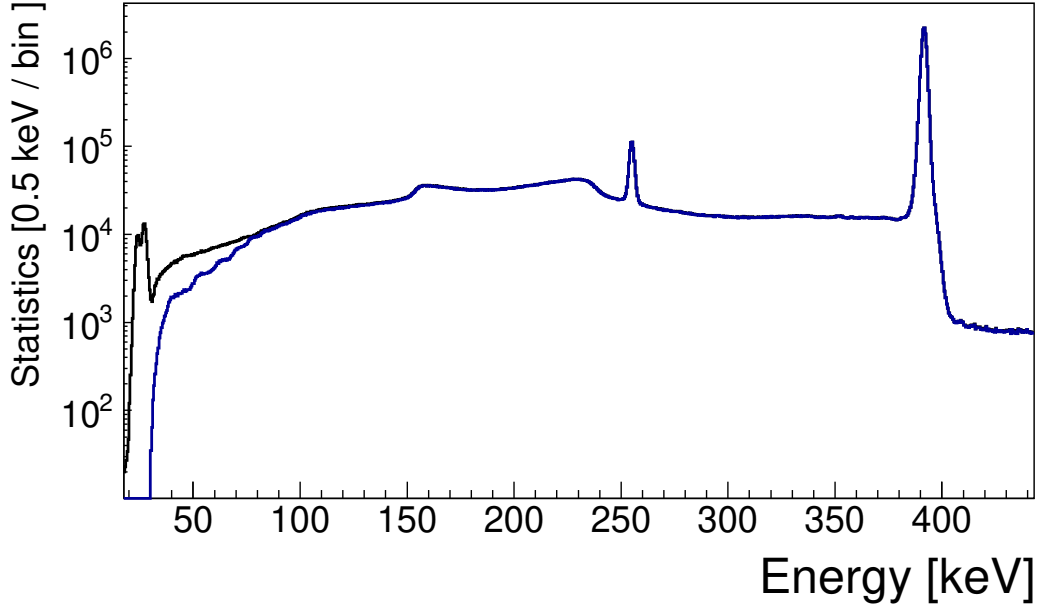


Fig. 8. (Color online) γ -ray spectrum of the β -decay of the ^{113}Sn source before (blue) and after (black) modified Pulse Shape Analysis for low energy event.

195 Figure 8 shows the γ -ray spectrum of the ^{113}Sn source placed at the center of
 196 AGATA with and without the corrections. The main γ -ray transitions at 255.1
 197 keV (2.11(8)% intensity) and 391.7 keV (64.9(1) % intensity) are visible. The
 198 $K\alpha$ (24 keV) and $K\beta$ (27 keV) are visible only after applying the correction
 199 proposed in the present work, it means forcing the Z position to 100 μm ,
 200 whereas they are suppressed by OFT using the standard PSA. As already
 201 mentioned, the low energy γ -rays measured at the back of the crystal coming
 202 from backing scattering are still rejected by the tracking algorithm after the
 203 correction, improving the peak-to-total ratio at low energy (≤ 500 keV). This
 204 can be illustrated by an analysis of the peak-to-total ratio using the ^{152}Eu
 205 source. Considering all ^{152}Eu lines between 15 keV and 500 keV, the procedure
 206 leads to an improved peak-to-total ratio from 41.01(2)% to 44.14(8)% mainly
 207 coming from the improved efficiency of the x-ray detection. An integration
 208 from 65 keV to 500 keV, i.e excluding the x-ray contribution, leads to a similar
 209 peak-to-total ratio: 36.44(2)% and 35.14(6)% without and with correction,
 210 respectively, demonstrating that the procedure does not influence the quality
 211 of the spectrum in the energy range.

212 5 Conclusion

213 The low energy response function of AGATA below 100 keV down to 20 keV
 214 has been evaluated using a large set of low energy radioactive sources. It was
 215 demonstrated that the present Pulse Shape Analysis returns a random position

216 distribution in the first layer of the AGATA crystal for low energy (≤ 100 keV)
217 interaction which highly impact the performances of the OFT tracking. New
218 approaches which will reduce the noise of low amplitude trace signal and the
219 time response will certainly improve the hit location at low energies. A simple
220 patch is presented in this paper that allows to minimize the problem.

221 References

- 222 [1] A. Bracco, G. Duchene, Z. Podolyk, P. Reiter, Gamma spectroscopy with
223 agata in its first phases: New insights in nuclear excitations along the
224 nuclear chart, Progress in Particle and Nuclear Physics 121 (2021) 103887.
225 doi:<https://doi.org/10.1016/j.pnpnp.2021.103887>.
226 URL
227 <https://www.sciencedirect.com/science/article/pii/S0146641021000417>
- 228 [2] V. I. Zagrebaev, Y. T. Oganessian, M. G. Itkis, W. Greiner, Superheavy nuclei
229 and quasi-atoms produced in collisions of transuranium ions, Phys. Rev. C 73
230 (2006) 031602. doi:10.1103/PhysRevC.73.031602.
231 URL <https://link.aps.org/doi/10.1103/PhysRevC.73.031602>
- 232 [3] A. Vogt, B. Birkenbach, P. Reiter, L. Corradi, T. Mijatović, D. Montanari,
233 S. Szilner, D. Bazzacco, M. Bowry, A. Bracco, B. Bruyneel, F. C. L. Crespi,
234 G. de Angelis, P. Désesquelles, J. Eberth, E. Farnea, E. Fioretto, A. Gadea,
235 K. Geibel, A. Gengelbach, A. Giaz, A. Görgen, A. Gottardo, J. Grebosz,
236 H. Hess, P. R. John, J. Jolie, D. S. Judson, A. Jungclaus, W. Korten, S. Leoni,
237 S. Lunardi, R. Menegazzo, D. Mengoni, C. Michelagnoli, G. Montagnoli,
238 D. Napoli, L. Pellegri, G. Pollarolo, A. Pullia, B. Quintana, F. Radeck,
239 F. Recchia, D. Rosso, E. Şahin, M. D. Salsac, F. Scarlassara, P.-A. Söderström,
240 A. M. Stefanini, T. Steinbach, O. Stezowski, B. Szpak, C. Theisen, C. Ur, J. J.
241 Valiente-Dobón, V. Vandone, A. Wiens, Light and heavy transfer products in
242 $^{136}\text{Xe} + ^{238}\text{U}$ multinucleon transfer reactions, Phys. Rev. C 92 (2015) 024619.
243 doi:10.1103/PhysRevC.92.024619.
244 URL <https://link.aps.org/doi/10.1103/PhysRevC.92.024619>
- 245 [4] B. Birkenbach, A. Vogt, K. Geibel, F. Recchia, P. Reiter, J. J. Valiente-
246 Dobón, D. Bazzacco, M. Bowry, A. Bracco, B. Bruyneel, L. Corradi, F. C. L.
247 Crespi, G. de Angelis, P. Désesquelles, J. Eberth, E. Farnea, E. Fioretto,
248 A. Gadea, A. Gengelbach, A. Giaz, A. Görgen, A. Gottardo, J. Grebosz,
249 H. Hess, P. R. John, J. Jolie, D. S. Judson, A. Jungclaus, W. Korten, S. Lenzi,
250 S. Leoni, S. Lunardi, R. Menegazzo, D. Mengoni, C. Michelagnoli, T. Mijatović,
251 G. Montagnoli, D. Montanari, D. Napoli, L. Pellegri, G. Pollarolo, A. Pullia,
252 B. Quintana, F. Radeck, D. Rosso, E. Şahin, M. D. Salsac, F. Scarlassara, P.-A.
253 Söderström, A. M. Stefanini, T. Steinbach, O. Stezowski, S. Szilner, B. Szpak,
254 C. Theisen, C. Ur, V. Vandone, A. Wiens, Spectroscopy of the neutron-rich
255 actinide nucleus ^{240}U following multinucleon-transfer reactions, Phys. Rev. C
256 92 (2015) 044319. doi:10.1103/PhysRevC.92.044319.
257 URL <https://link.aps.org/doi/10.1103/PhysRevC.92.044319>

258 [5] S. Akkoyun, A. Algora, B. Alikhani, F. Ameil, G. de Angelis, L. Arnold,
259 A. Astier, A. Ataac, Y. Aubert, C. Aufranc, A. Austin, S. Aydin, F. Azaiez,
260 S. Badoer, D. Balabanski, D. Barrientos, G. Baulieu, R. Baumann, D. Bazzacco,
261 F. Beck, T. Beck, P. Bednarczyk, M. Bellato, M. Bentley, G. Benzoni,
262 R. Berthier, L. Berti, R. Beunard, G. L. Bianco, B. Birkenbach, P. Bizzeti,
263 A. Bizzeti-Sona, F. L. Blanc, J. Blasco, N. Blasi, D. Bloor, C. Boiano,
264 M. Borsato, D. Bortolato, A. Boston, H. Boston, P. Bourgault, P. Boutachkov,
265 A. Bouty, A. Bracco, S. Brambilla, I. Brawn, A. Brondi, S. Broussard,
266 B. Bruyneel, D. Bucurescu, I. Burrows, A. Burger, S. Cabaret, B. Cahan,
267 E. Calore, F. Camera, A. Capsoni, F. Carrio, G. Casati, M. Castoldi,
268 B. Cederwall, J.-L. Cercus, V. Chambert, M. E. Chambit, R. Chapman,
269 L. Charles, J. Chavas, E. Clement, P. Cocconi, S. Coelli, P. Coleman-Smith,
270 A. Colombo, S. Colosimo, C. Commeaux, D. Conventi, R. Cooper, A. Corsi,
271 A. Cortesi, L. Costa, F. Crespi, J. Cresswell, D. Cullen, D. Curien, A. Czermak,
272 D. Delbourg, R. Depalo, T. Descombes, P. Desesquelles, P. Detistov, C. Diarra,
273 F. Didierjean, M. Dimmock, Q. Doan, C. Domingo-Pardo, M. Doncel,
274 F. Dorangeville, N. Dosme, Y. Drouen, G. Duchene, B. Dulny, J. Eberth,
275 P. Edelbruck, J. Egea, T. Engert, M. Erduran, S. Erturk, C. Fanin, S. Fantinel,
276 E. Farnea, T. Faul, M. Filliger, F. Filmer, C. Finck, G. de France, A. Gadea,
277 W. Gast, A. Geraci, J. Gerl, R. Gernhauser, A. Giannatiempo, A. Giaz,
278 L. Gibelin, A. Givechev, N. Goel, V. Gonzalez, A. Gottardo, X. Grave,
279 J. Grebosz, R. Griffiths, A. Grint, P. Gros, L. Guevara, M. Gulmini, A. Gorgen,
280 H. Ha, T. Habermann, L. Harkness, H. Harroch, K. Hauschild, C. He,
281 A. Hernandez-Prieto, B. Hervieu, H. Hess, T. Huyuk, E. Ince, R. Isocrate,
282 G. Jaworski, A. Johnson, J. Jolie, P. Jones, B. Jonson, P. Joshi, D. Judson,
283 A. Jungclaus, M. Kaci, N. Karkour, M. Karolak, A. Kaskas, M. Kebbiri,
284 R. Kempley, A. Khaplanov, S. Klupp, M. Kogimtzis, I. Kojouharov, A. Korichi,
285 W. Korten, T. Kroell, R. Krucken, N. Kurz, B. Ky, M. Labiche, X. Lafay,
286 L. Lavergne, I. Lazarus, S. Leboutelier, F. Lefebvre, E. Legay, L. Legeard,
287 F. Lelli, S. Lenzi, S. Leoni, A. Lermilage, D. Lersch, J. Leske, S. Letts,
288 S. Lhenoret, R. Lieder, D. Linget, J. Ljungvall, A. Lopez-Martens, A. Lotode,
289 S. Lunardi, A. Maj, J. van der Marel, Y. Mariette, N. Marginean, R. Marginean,
290 G. Maron, A. Mather, W. Meczynski, V. Mendez, P. Medina, B. Melon,
291 R. Menegazzo, D. Mengoni, E. Merchan, L. Mihailescu, C. Michelagnoli,
292 J. Mierzejewski, L. Milechina, B. Million, K. Mitev, P. Molini, D. Montanari,
293 S. Moon, F. Morbiducci, R. Moro, P. Morrall, O. Moller, A. Nannini, D. Napoli,
294 L. Nelson, M. Nespolo, V. Ngo, M. Nicoletto, R. Nicolini, Y. L. Noa, P. Nolan,
295 M. Norman, J. Nyberg, A. Obertelli, A. Olariu, R. Orlandi, D. Oxley, C. Ozben,
296 M. Ozille, C. Oziol, E. Pachoud, M. Palacz, J. Palin, J. Pancin, C. Parisel,
297 P. Pariset, G. Pascovici, R. Peghin, L. Pellegrini, A. Perego, S. Perrier, M. Petcu,
298 P. Petkov, C. Petrache, E. Pierre, N. Pietralla, S. Pietri, M. Pignanelli,
299 I. Piqueras, Z. Podolyak, P. L. Pouhalec, J. Pouthas, D. Pugnere, V. Pucknell,
300 A. Pullia, B. Quintana, R. Raine, G. Rainovski, L. Ramina, G. Rampazzo, G. L.
301 Rana, M. Rebeschini, F. Recchia, N. Redon, M. Reese, P. Reiter, P. Regan,
302 S. Riboldi, M. Richer, M. Rigato, S. Rigby, G. Ripamonti, A. Robinson,
303 J. Robin, J. Roccaz, J.-A. Ropert, B. Rosse, C. R. Alvarez, D. Rosso, B. Rubio,
304 D. Rudolph, F. Saillant, E. Sahin, F. Salomon, M.-D. Salsac, J. Salt, G. Salvato,

- 305 J. Sampson, E. Sanchis, C. Santos, H. Schaffner, M. Schlarb, D. Scraggs,
 306 D. Seddon, M. Senyigit, M.-H. Sigward, G. Simpson, J. Simpson, M. Slee,
 307 J. Smith, P. Sona, B. Sowicki, P. Spolaore, C. Stahl, T. Stanios, E. Stefanova,
 308 O. Stezowski, J. Strachan, G. Suliman, P.-A. Soderstrom, J. Tain, S. Tanguy,
 309 S. Tashenov, C. Theisen, J. Thornhill, F. Tomasi, N. Toniolo, R. Touzery,
 310 B. Travers, A. Triossi, M. Tripon, K. Tun-Lanoe, M. Turcato, C. Unsworth,
 311 C. Ur, J. Valiente-Dobón, V. Vandone, E. Vardaci, R. Venturelli, F. Veronese,
 312 C. Veysiére, E. Viscione, R. Wadsworth, P. Walker, N. Warr, C. Weber,
 313 D. Weisshaar, D. Wells, O. Wieland, A. Wiens, G. Wittwer, H. Wollersheim,
 314 F. Zocca, N. Zamfir, M. Zieblinski, A. Zucchiatti, Agata advanced {GAMMA}
 315 tracking array, Nuclear Instruments and Methods in Physics Research Section
 316 A: Accelerators, Spectrometers, Detectors and Associated Equipment 668
 317 (2012) 26 – 58. doi:<http://dx.doi.org/10.1016/j.nima.2011.11.081>.
- 318 [6] A. Lopez-Martens,
 319 K. Hauschild, A. Korichi, J. Roccaz, J.-P. Thibaud, γ -ray tracking algorithms:
 320 a comparison, Nuclear Instruments and Methods in Physics Research Section
 321 A: Accelerators, Spectrometers, Detectors and Associated Equipment 533 (3)
 322 (2004) 454 – 466. doi:<http://dx.doi.org/10.1016/j.nima.2004.06.154>.
- 323 [7] B. D. Canditiis, G. Duchene, M. Sigward, F. Didierjean, M. Ginz,
 324 D. Ralet, Full-volume characterization of an agata segmented hpge gamma-
 325 ray detector using a 152eu source, Eur. Phys. J. A 57 (2021) 223.
 326 doi:<https://doi.org/10.1140/epja/s10050-021-00537-1>.
 327 URL
 328 <https://link.springer.com/article/10.1140/epja/s10050-021-00537-1>
- 329 [8] A. Wiens, H. Hess, B. Birkenbach, B. Bruyneel, J. Eberth, D. Lersch,
 330 G. Pascovici, P. Reiter, H.-G. Thomas, The agata triple cluster detector,
 331 Nuclear Instruments and Methods in Physics Research Section A: Accelerators,
 332 Spectrometers, Detectors and Associated Equipment 618 (1) (2010) 223–233.
 333 doi:<https://doi.org/10.1016/j.nima.2010.02.102>.
 334 URL
 335 <https://www.sciencedirect.com/science/article/pii/S0168900210003384>
- 336 [9] G. Duchene, F. Beck, P. Twin, G. de France, D. Curien, L. Han, C. Beausang,
 337 M. Bentley, P. Nolan, J. Simpson, The clover: a new generation of composite
 338 ge detectors, Nuclear Instruments and Methods in Physics Research Section
 339 A: Accelerators, Spectrometers, Detectors and Associated Equipment 432 (1)
 340 (1999) 90–110. doi:[https://doi.org/10.1016/S0168-9002\(99\)00277-6](https://doi.org/10.1016/S0168-9002(99)00277-6).
 341 URL
 342 <https://www.sciencedirect.com/science/article/pii/S0168900299002776>
- 343 [10] E. Farnea, F. Recchia, D. Bazzacco, T. Kroell, Z. Podolyak, B. Quintana,
 344 A. Gadea, Conceptual design and monte carlo simulations of the agata array,
 345 Nuclear Instruments and Methods in Physics Research Section A: Accelerators,
 346 Spectrometers, Detectors and Associated Equipment 621 (120133) (2010) 331
 347 – 343. doi:<http://dx.doi.org/10.1016/j.nima.2010.04.043>.
- 348 [11] J. Ljungvall, Pulse-shape calculations and applications using the agatagefem

349 software package, Eur. Phys. J. A 57 (2021) 198. doi:10.1140/epja/s10050-021-
350 00512-w.
351 URL <https://doi.org/10.1140/epja/s10050-021-00512-w>