NEW DETECTION TECHNIQUES FOR GAMMA RADIATIONS AND POSSIBLE APPLICATIONS

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Abstract. *One presents the newest detection method for gamma radiation, based on the use of the segmented hyperpure Ge (HPGe) detectors, which are able to give information on both the energy and position of each Compton interaction of a photon within the detector. Thus, knowing the interaction points of a photon in a detector (or an array of detectors) one can completely reconstruct the history of its absorption, considerably improving the performance of the detection in sensitivity and efficiency. The Eeuropean project AGATA, based on a collaboration of some 45 institutions from 12 countries, which constructs such an "ultimate" detector to be used for gamma-ray spectroscopy at the future nuclear physics facilities, is briefly presented. Due to their properties, the segmented HPGe detectors constitute true γ-ray imaging setups, with great applicative potential in different domains. Imaging tests with an AGATA prototype detector and possible gamma imaging applications are briefly described.*

Keywords: Gamma radiation detection; segmented HPGe detectors; Compton scattering; imaging.

1. Introduction

The nuclear spectroscopy has as purpose the investigation of a very complicated quantum mechanical system: the atomic nucleus, which is composed of up to a few hundreds of strongly interacting nucleons. The nuclear structure studies aim at understanding the nuclear excitations (nuclear levels). One of the most powerful experimental tools to do this, which contributed the most to our present knowledge, is the precision γ-ray spectroscopy, which studies the nuclear levels populated in different nuclear reactions or decays through their electromagnetic (gamma) decay. Developing γ-ray detectors with high efficiency and energy resolution has been a continuous challenge for the nuclear structure community, and this process has often required reaching new technological achievements, which could be used in applications of nuclear methods in many other domains.

The gamma-ray detectors made of hyper-pure germanium crystals (HPGe) offer the best energy resolution. However, the energy spectra registered with such simple detectors are complicated, due to the complexity of the interaction

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of the photons with the matter of the detector. A gamma-ray (photon) leaves its energy in the detector as a result of the processes shown in Fig. 1. If the photon transfers its full energy to one electron (photoelectric effect) then the electron will leave this energy within the crystal by creating a number of electron-hole pairs which will be collected by the electric field polarizing the detector, the resulting impulse being proportional to the photon energy. This is the most desirable situation and the resulting spectrum consists of the "photopeak" only. A second process, the Compton scattering, becomes very probable at energies above 100-200 keV: the photon scatters off electrons, leaving only part of its energy, and we may have several such scatterings; if one of the scattered photons leaves the detector, then we register less energy and the resulting spectrum becomes more complicated, with a continuous Compton "tail" at energies smaller than the photopeak.

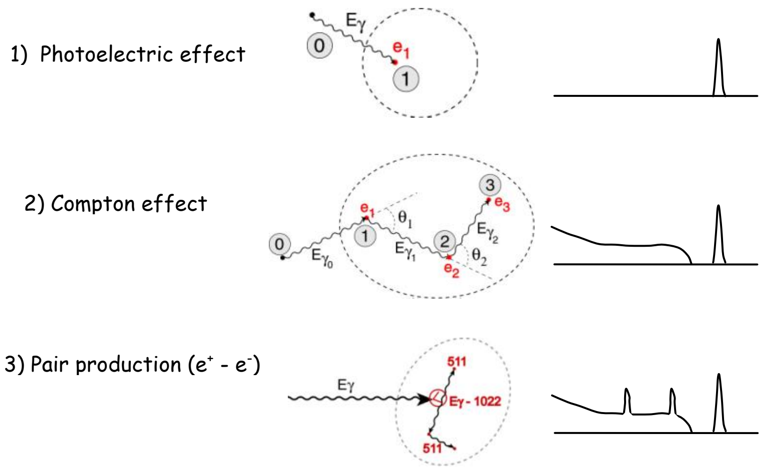


Figure 1 Processes by which a gamma-ray (photon) interacts with a Ge detector; the left size shows the corresponding response (energy spectrum).

When the energy of the incident photon is larger than 1022 keV, the third process,production of e^+-e^- pairs, starts to compete; the annihilation of the positron produces a pair of 511 keV photons, their possible escape from detector giving, in addition, two "escape peaks" in the spectrum. During the last few decades,in order to improve the quality of the spectra, namely the "peak-to-total" ratio, anti-Compton (or escape suppression) shields have been developed: the Ge detector is surrounded by another detector (shield) which does not need good energy resolution (like scintillator detectors, NaI(Tl) or, more recently, BGO – bismuth germanate), a coincidence between the two detectors is made, and pulses in the central detector are registered only in the absence of a coincidence (therefore Compton scattering events which leave the detector are rejected). This procedure may reduce very much the Compton continuum of the spectra. One should note that in nuclear spectroscopy, besides good energy resolution and peak-to-total ratio, one often needs to have good sensitivity in detecting events of high γ-ray multiplicity – and this can be improved only by increasing the number of detectors (the granularity) of the detection systems (because, at the limit, just one big detector surrounding the source works as a "calorimeter", summing up the energies of all γ-rays from that event, without being able to distinguish them). There is another factor which requires the use of more Ge detectors which are not too large in size: in many nuclear reactions, the final nuclei, which we want to study by their γ-decay, are not at rest with respect to the detector, but move, sometimes with a considerable velocity (up to tens of percents of the light velocity). Then, the photons emitted in flight are Doppler shifted in energy (for not so large velocities, we have, in first order: $E_\gamma = E_0\ (1+ (v/c)\cos\theta)$, where v is the velocity of the recoiling nucleus, and θ the angle between the recoil direction and that of the emitted photon). A "large" detector (covering a wide angle) will obviously lead to a considerable Doppler widening of the γ-ray peaks, eventually making good spectroscopy impossible.

In order to increase the absolute efficiency of a gamma-ray detection system, the only solution is to increase the number of detectors in a geometry approximating as much as possible a 4π solid angle (a spherical shell, or a "ball"). A number of such systems were constructed, most of them comprising HPGe detectors of different geometries, each one with anti-Compton shield, packed as closely as possible in spherical geometry, a few examples being EUROBALL (in Europe) – 239 Ge crystals and a 120 Ge detectors shell[1], GAMMASPHERE – 110 detectors (in the USA) [2], GASP (Italy) – 40 Ge crystals with anti-Compton shields and an 80 BGO elements shell [3]. Their absolute (total) photopeak efficiency does not exceed 10%, since a lot of space is taken away by the anti-Compton shields, and the photons only partially absorbed into the Ge detectors are thrown away. On the other hand, such systems cannot be used with relativistic beams of nuclei, because due to the large recoil velocities the Doppler widening becomes considerable. By decreasing the detector sizes one would have to increase their number too much (to more than 1000) which is both costly, and unpractical.

2. Segmented Ge detectors; the AGATA detector array.

Performing precise γ-ray spectroscopy at the future facilities with radioactive ion-beams requires the optimization of several, sometimes conflicting properties, such as: maximum photopeak efficiency; good spectral response (peak-to-total ratio); very good angular resolution for the emission direction of the detected γ-quanta (to reduce the Doppler effects); the system should stand very high counting rates (large background above weak reaction channels of interest); a system with enough free inner space (in order to allow additional detection systems, such as charged particle detectors).

All these features can be simultaneously achieved by a new generation of spectrometers, built from a close-packed arrangement of *segmented* (γ-ray tracking) HPGe detectors, which resembles a 4π shell of large Ge crystals. Such a system, named AGATA (Advanced GAmma Tracking Array) is being built by a collaboration of 45 institutions from 12 European countries (including Romania) [4]. A similar instrument, named GRETA (Gamma Ray Energy Tracking Array) is being built in the USA [5]. A schematic view of AGATA and its main characteristics are shown in Fig. 2.

Main features of AGATA

Efficiency: 40% (M_γ =1) 25% (M_γ =30)
today's arrays ~10% 5%

Peak/Total: 55% (M_γ=1) 45% (M_γ=30)
today ~55% 40%

Angular Resolution: ~1° →FWHM (1 MeV, v/c=50%) ~ 6 keV !!!
today ~40 keV

Rates: 3 MHz (M_γ=1) 300 kHz (M_γ =30)
today 1 MHz 20 kHz

- 180 large volume 36-fold segmented Ge crystals in 60 triple-clusters
- Digital electronics, pulse shape analysis; position sensitivity (γ-ray tracking)

Figure 2 Schematic layout of AGATA and its performances [4]. The detectors are grouped in "triple clusters", all detectors in a cluster being cooled by a common cryostat.

AGATA comprises 180 tapered Ge crystals of hexaconical shape, 9 cm long and about 8 cm diameter at the base, each one segmented in 36 parts. The segmentation of the detectors gives the possibility of operating them in a novel way: γ-ray tracking. This segmentation is shown in Fig. 3 and it is realized by dividing the surface of the detector in electrically insulated portions, as shown (6 sectors x 6 slices). In this way, although the detector is not physically divided, there are 36 independent electrical fields in the volume of the detector, between the common anode and the 36 cathodes which provide independent signals, each segment providing an output signal as an independent detector. This segmentation allows the identification of the position of a photon interaction with the crystal with a precision of a few millimeters, giving these detectors a new quality: sensitivity to the position of the photon interaction(s). This allows two major achievements: (i) tracking of a γ-ray thorough the detector(s), that is, reconstruction of the trajectory of a photon by following its successive Compton scatterings and the final photoelectric absorption, which means one can get, practically for any photon (except for those which partially escape from the detector system), its full energy, therefore a very good photopeak efficiency and peak-to-total ratio; (ii) by determining with good accuracy the position of the first point of interaction (the angle at which the photon is detected with respect to the beam direction) one can perform very good Doppler correction, even for very large recoil velocities.

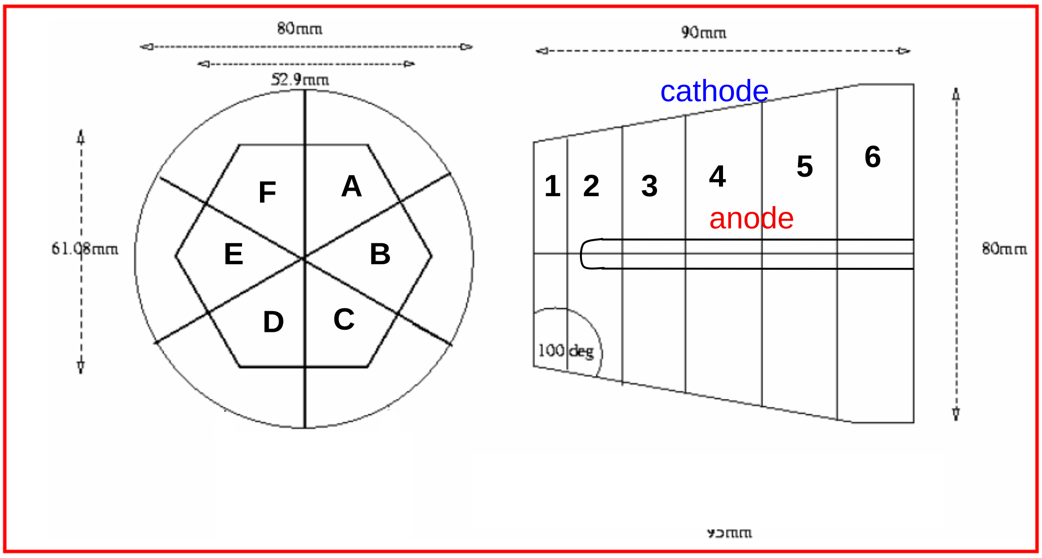


Figure 3 The segmentation of a typical AGATA detector [4].

The exploitation of the position sensitivity of a segmented Ge detector relies on the analysis of the shape of the pulses provided by its different segments, which are stored and processed by fast digital electronics. The interaction points of the γ rays in the detector can be localized with a much higher precision than the physical segmentation if the spatial information contained in the detector signals is exploited. The shape of the segment signals (registered with fast digital converters) depends on the interaction position, since it results from the electrons and holes generated by the photo- or Compton- electron which induce image charges of opposite signs on the detector electrodes. The charge carriers drift towards the electrodes, causing changes into the amount of the image charges and therefore flows of currents into or out of the electrodes. The induced charge is distributed over several electrodes (those closest to the interaction) and depends on the distance to those electrodes. An example of pulses measured with an AGATA detector is shown in Fig. 4; the measured pulses are compared with calculated ones, following the indicated algorithm [6]. The precision in the determination of the position of the interaction for AGATA detectors is found to be around 5 mm.

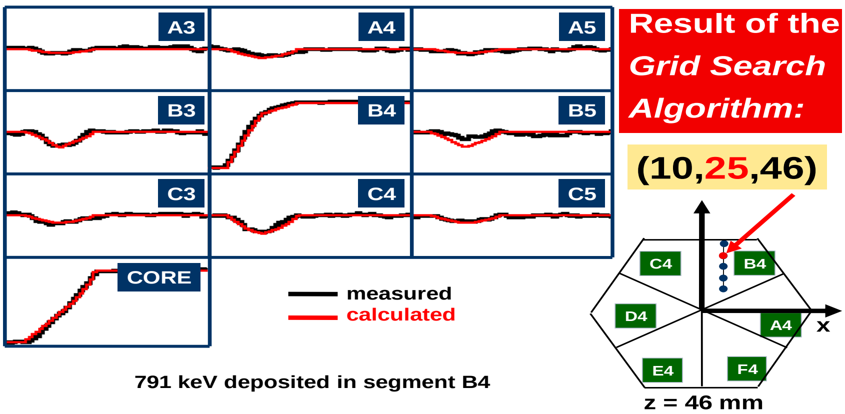


Figure 4 Example of pulse-shape analysis of an interaction in an AGATA detector. A photon left 791 keV in segment B4, and the pulses given by this segment and its neighbors (see Fig. 3) are shown. The continuous lines are calculated with the specified algorithm, for different interaction positions. The best fit is obtained for the position (x,y,z) = (10,25,46) (relative coordinates in mm); calculations with y=20 or 30 mm give much worse fits (ref. [6]).

With different algorithms of *pulse-shape analysis* [6,7] one can determine the position (x,y,z) of any interaction point of a photon. The next step is to use this information for *tracking* of the γ rays. For each photon we will have a number of interaction points characterized by the energy left in that point and its geometric coordinates. If there are more photons in the event, we will have a set of points (E_i,x_i,y_i,z_i). A first problem is to determine how many photons interacted with the detector. There are different algorithms to do this *clustering*, and they are generally based on the fact that a photon which hits the detector in a certain point will produce a number of interactions within a certain angle around the initial direction, or within a certain distance from the first point, therefore one may first make clusters of points, each one resumably representing one photon. The next step is to validate these clusters by trying to find a sequence of points which obeys the laws of the Compton scattering, and ends with a photoelectric absorption. This is the γ-ray *tracking* procedure, for which there are also different proposed algorithms [8], and it results in a number of photons, the essential result being that for each photon one determines the full *energy* and the *position of the first interaction point*. As a result of the pulse-shape analysis and tracking procedures which are typical to the segmented detectors, the performances of the detector array are unprecedented (see Fig. 2), AGATA being the most advanced γ-ray detector which fully responds to the requirements of the spectroscopy of most exotic nuclear species at the future facilities based on accelerated radioactive ions. The unique features of the segmented detectors recommend them for many other applications, especially due to their capability to perform γ-ray imaging.

3. Gamma-ray imaging with segmented Ge detectors

Imaging with gamma rays is a very important method in several domains, such as:

- *High-energy astrophysics*: aiming to correlate a detected photon to a source object known from more precise observations in other wavelength ranges. This is extremely important for understanding problems related to explosive processes and nucleosynthesis.
- *(Bio)medical research*: (i) localization of radioactive tracers in the body; (ii) monitor changes in the tracer distribution (dynamics); (iii) cancer diagnosis; (iv) targeted radiation therapy.
- *Security*: (i) nuclear non-proliferation/terrorism; (ii) detection of radioactive material contraband; (iii) stockpile stewardship; (iv) nuclear waste monitoring and management.
- *Non-destructive industrial assessments*: determination of material density distribution between source and detector.

Historically, the first γ-ray imaging systems were collimator-based systems. As an example, in the Anger cameras [9] one uses a parallel-hole collimator between the object and a system(array) of detectors, and processes the response of each detector as a function of its position to the holes. One may also use a screen with a pinhole, like the first optical cameras, or more complicated systems which use coded or modulation apertures (in space or time/frequency). An example of collimator-less system is the PET (positron emission tomography) [9] which uses the property that a positron annihilation produces two 511 keV photons which fly exactly in opposite directions (at 180^0). The position-sensitive HPGe detectors constitute also collimator-less imaging devices, based on the Compton tracking principle. This principle [6,11] is illustrated in Fig. 5. Assume a point source - represented by a star in Fig. 5(a), which emits a photon that scatters under the angle θ in the detector (the Compton formula of the energy after scattering is also given in part (a) of the figure). We know the initial energy E_γ and measure (by tracking methods) the energy $E_{\gamma'}$ and the angle θ. From just one event like this we can say that the source is somewhere on the cone with half-angle θ around the direction of the scattered photon. Registering more photons means registering more such "Compton" cones. These cones, intersected with a sphere (b) or a plane (c), will intersect each other in a region which defines the image of the source – the higher the statistic (the number of registered photons) and the accuracy in the determination of θ, the sharper (closer to a "point") will be the image (d). Note that we can use for imaging in this way just one segmented detector (or a system of such detectors) – and that it constitutes an *omni-directional (4π) camera*, that is, we can determine both the direction of the source, and its image, no matter where the source is placed with respect to the detector (unlike the collimator–based systems which must have a precise orientation with respect to the source). Compton effect–based cameras were used since a long time in astrophysics – the so-called Compton telescopes. Actually, older generations of such telescopes used two layers of detectors, one being used as a scatterer. An example of very successful such telescope is COMPTEL [10] which was placed on an orbital station and for many years mapped the sky and established the most important objects in Universe which emit γ-rays within different energy windows. Now, however, it is clear that just one single segmented detector can be used as a γ-ray camera. This possibility was tested on different segmented detectors, and, recently, also on an AGATA prototype detector [6].

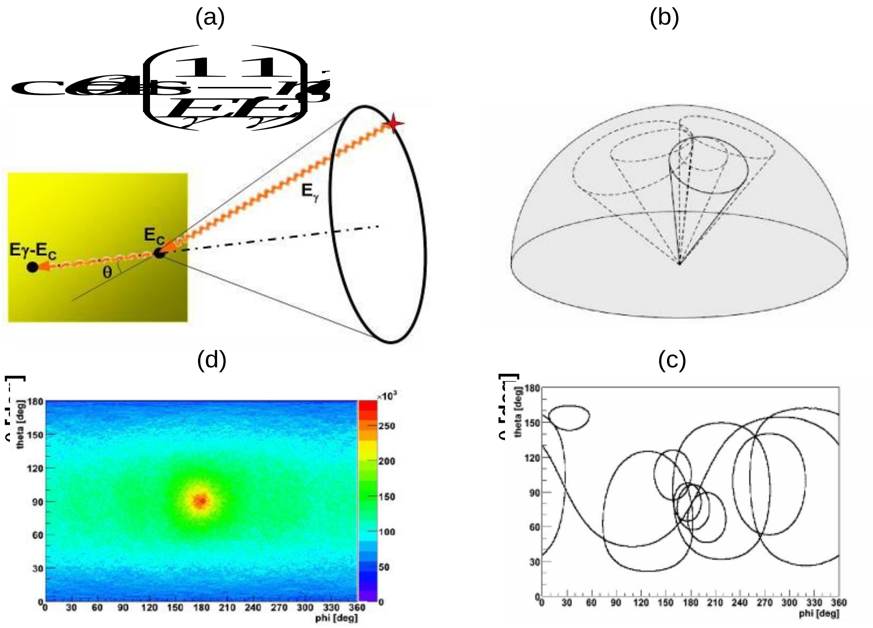
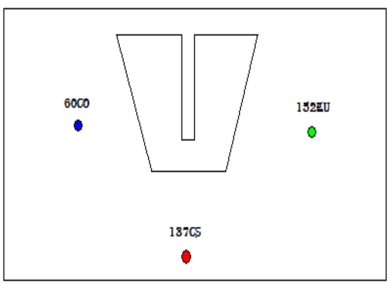


Figure 5 Principle of the γ-ray imaging with a segmented Ge detector.

This imaging test with an AGATA detector is illustrated below.

- Used crystal: **AGATA S001**
- Sources: **^{60}Co , ^{152}Eu, ^{137}Cs**
- Acquisition time: 24 hours



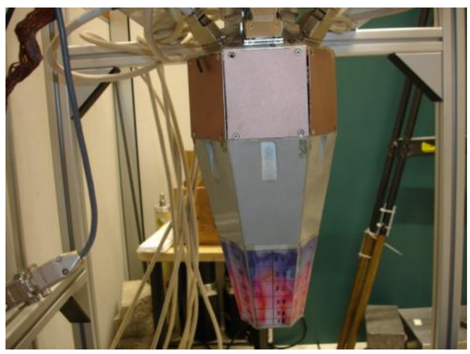


Figure 6 Experimental arrangement for γ-ray imaging with an AGATA detecto [6].

Three different point-like γ-ray emmiting sources were placed around one symmetric AGATA crystal, as shown in Fig. 6: ^{60}Co and ^{152}Eu, placed around the middle of the crystal, on both sides of it (approximately at 180 degrees), and ^{137}Cs placed in front of the detector, on its axis (θ = 0). By applying the method exposed above, using γ-rays characteristic of each source, one could simultaneously determine the image of each source. Such a result is shown in Fig. 7, in a (θ,φ) plane, where one can see that the first two sources are found indeed at about the same value of θ, but φ values which differ by about 180 degrees, and their image has a certain sharpness (calculations show that the position resolution in the tracking process was about 5 mm FWHM). For the third source (^{137}Cs) one does not get a sharp image in φ, because for θ = 0 φ is not defined. Also (not shown) for the 1461 keV background radiation of ^{40}K (from the concrete walls) one does not get any "image" (the plane is uniformly filled) since it came from all directions. The sharpness of the images can be improved by using different numerical algorithms. Other tests with segmented Ge detectors showed that such 4π cameras can be used to find "hidden" sources, or to map a multitude of isotopes in a certain area [12]. Note that due to their good energy resolution, the segmented Ge detectors can be used to simultaneously map different isotopes, by gating on their characteristic γ-rays.

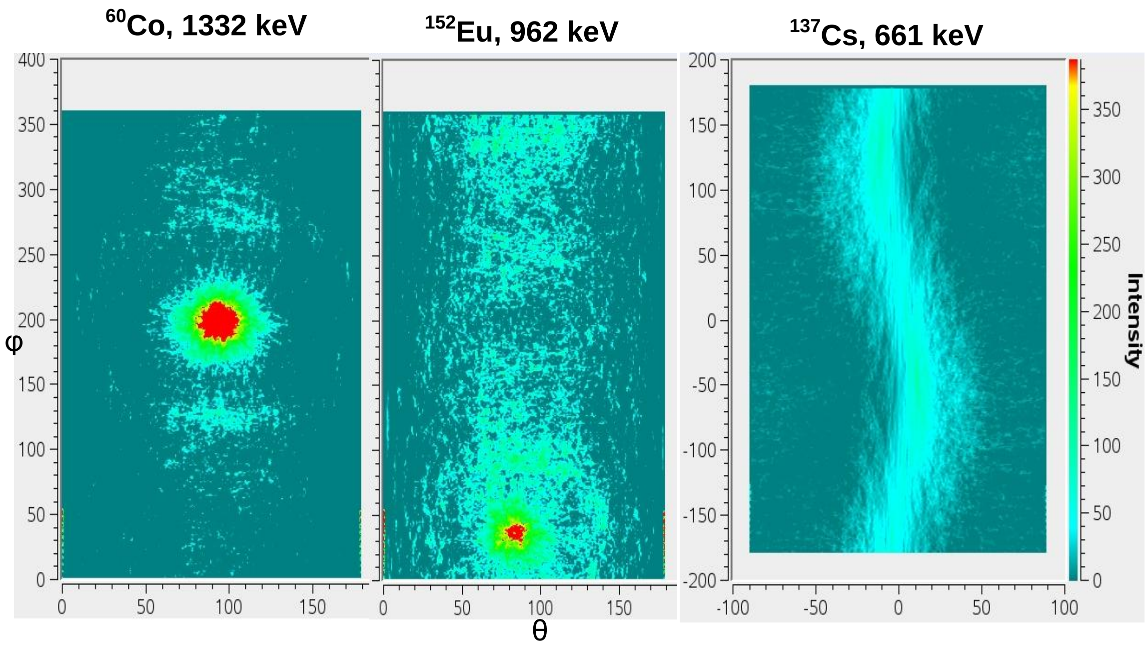


Figure 7 Images of the three sources placed around an AGATA detector as shown in Fig. 6. The images shown here were obtained by tracking on the radiations with the indicated energies [6].

4. Conclusions

It was presented how new technologies allow a new detection method for the gamma radiations. These are: the segmented HPGe detectors, fast electronic digitizers, pulse-shape analysis, and tracking of the γ-rays. The detection method based on pulse-shape analysis and tracking leads to unprecedented qualities of the γ-ray detectors; the AGATA European project was briefly presented. These performances are a result of the fact that while older detection systems wasted the Compton scattered gammas, the new technologies allow now to track them.

While the development of AGATA is fully devoted to basic research at the frontiers of the knowledge, it is clear that the segmented detectors have properties that recommend them for applications in many other fields. In particular, it is described the novel imaging technique based on the Compton scattering. A test of the imaging performances of an AGATA prototype detector was presented. The Compton imaging does not require collimating systems and therefore has much higher sensitivity than other methods. The sensitivity and position resolution attained with Ge detectors is adequate for medical and safety applications. The energy resolution provides very good isotope identification, and, in addition, such a detector offers omni-directional imaging. Such detectors can be used for accurate mapping of the spatial distribution of gamma radiations.

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