Eur. Phys. J. A (2025) 61:100
https://doi.org/10.1140/epja/s10050-025-01574-w

THE EUROPEAN PHYSICAL JOURNAL A

Regular Article

New encapsulation technology for HPGe detectors

P. Reiter[1a], **J. Eberth**[1], **H. Hess**[1], **S. Thiel**[1]

Institut für Kernphysik, University of Cologne, Zülpicher Strasse 77, 50937 Köln, Germany

Received: 25 February 2025 / Accepted: 15 April 2025

Communicated by Wolfram Korten

Abstract A new encapsulation technology for HPGe detectors operating in ultra high vacuum or in inert atmosphere of high purity gas was developed. The high-purity Ge detectors for radiation detection is based on a reusable receptacle or enclosure. The main mechanical parts, the detector capsule and the lid are connected in a vacuum-tight manner with an elastic metallic seal which works in the wide temperature range from liquid nitrogen to +105° with a leak rate below 10^{-10} mbar·l/s. A UHV quality below 10^{-7} mbar or a gas purity better than N5.0 (99.999%) is ensured. The capsule and the lid can be dismounted manually without machining. The mechanical parts can be reused maintaining the performance in the whole temperature range and the requested low leak rate. The new technology is already being used for various types of detectors. In addition to the advantages, the results obtained do not show any changes in the excellent properties of HPGe detectors in terms of energy resolution or other essential features.

1 Introduction

High-Purity Germanium (HPGe) detectors are renowned for their exceptional energy resolution and high detection efficiency for gamma radiation, making them indispensable tools in various fields, including nuclear physics, radiation protection, environmental monitoring, non-destructive material analysis, industrial production control, and space research. The performance of these detectors is critically dependent on their operational environment, necessitating cooling to temperatures as low as 77 K to mitigate thermal noise in the germanium diodes. This cooling is typically achieved through the use of vacuum cryostats, which not only facilitate the required low temperatures but also safeguard the sensitive surfaces of the detectors from contamination. Alternatively, HPGe detectors can be operated in an inert atmosphere of high-purity gas, further enhancing their performance under controlled conditions.

However, the delicate nature of HPGe detectors, especially their surface passivation layer, makes them highly vulnerable to environmental influences such as moisture, temperature fluctuations, and mechanical stress. This susceptibility can significantly degrade their performance over time, necessitating robust protection solutions to maintain their long-term stability and operational efficiency. Encapsulation plays a critical role in safeguarding HPGe crystals from these external impacts. By providing a protective housing, encapsulation ensures that the surface remains intact, preventing contamination and damage from exposure to harsh environmental conditions. In addition to surface protection, encapsulation can enhance the detection efficiency of composite detectors. For instance, in advanced multi-detector systems such as the EUROBALL Cluster, encapsulation was used to protect seven individual HPGe detectors, allowing them to function as a unified, highly sensitive system.

Despite its advantages, traditional encapsulation techniques – especially for segmented detectors – have limitations and there remains a need for improved technologies to enhance the durability and functionality of HPGe detectors. Established methods often involve hermetically sealed aluminium capsules that are closed using electron beam welding techniques. While this approach has been effective, it presents significant drawbacks, particularly for segmented detectors which are subject to much higher maintenance needs and repair work inside the capsule. One of the key disadvantages of these older methods is that the protective capsule must be destroyed if a detector requires repair, leading to a loss of both time and material resources. Furthermore, the welding procedure used in the older techniques can compromise mechanical accuracy, resulting in reduced alignment precision and potentially diminishing the over-

[a] e-mail: preiter@ikp.uni-koeln.de (corresponding author)

all performance of the detector system. As the demands for higher performance and reliability grow, it becomes increasingly apparent that more efficient encapsulation methods are necessary to overcome these challenges, ensuring both the durability and functionality of HPGe detectors in complex applications.

In this paper, we present a novel encapsulation technology designed to address these limitations, enhancing the reliability and maintainability of HPGe detectors while preserving their high-performance characteristics. The publication describes a receptacle or receiving container for a detector working in an ultra-high vacuum or in a protective gas atmosphere made of high-purity gas, with a receiving part (capsule) for the detector and a cover (lid) for gas-tight sealing of the receiving space. The technology is not limited to HPGe detectors but can be adapted to other semiconductor detectors for high-resolution γ spectroscopy, with diodes made of silicon, cadmium zinc telluride, gallium arsenide or cadmium telluride generally being used.

The paper is organized in the following way. The next chapter provides an overview of several encapsulated HPGe detectors. The importance of encapsulation in protecting the sensitive components from environmental factors is emphasized. The chapter motivates the need for improved encapsulation technologies. The third chapter is concerned with the novel encapsulation technique. It is divided into three subchapters: (i) the innovative mechanical design of the new encapsulation technique. The focus is on achieving a balance between protection and accessibility for maintenance and repairs. (ii) The section outlines the vacuum properties of the new encapsulation technique which are crucial for maintaining the performance of HPGe detectors at low temperatures. (iii) New detectors for AGATA (Advanced GAmma Tracking Array) and the Miniball spectrometer are put into operation. The specific adaptations made for these systems and how these new detectors compare to their predecessors in terms of performance and reliability are given. The paper concludes with a summary of the key findings and implications of the new encapsulation technology.

2 Encapsulated HPGe detectors

Hermetically encapsulated detectors were developed to build compact multi-detector arrays like EUROBALL [1,2], Miniball [3,4], or the Advanced Gamma Tracking Array (AGATA) [5] optimized for highest detection efficiency and large solid angle coverage for nuclear physics γ-ray spectroscopy experiments. The development and construction of the EUROBALL spectometer included the development of the hermetical encapsulation of the individual HPGe crystals detectors [6] to facilitate the production and the maintenance of large clusters of detectors. The encapsulation technology was needed in order not to damage the very sensitive and delicate intrinsic surface of the HPGe crystals during assembly of the HPGe in the cryostat or later during possible repairs. In particular, broken FETs, annealing of neutron induced radiation damage and problems with the protecting vacuum are typical difficulties affecting the reliable operation of cluster detectors. The technique of hermetically closed, vacuum-tight encapsulated HPGe detectors was adopted successfully for the EUROBALL, Miniball and AGATA spectrometers. Three (Miniball and AGATA) or seven (Euroball) of the individually encapsulated detectors were mounted in a common cryostat. In this way the overall reliability of the detector systems has been increased significantly allowing long term operation over years.

The receiving container of the EUROBALL, Miniball or AGATA detectors are built out of aluminum. The shape of the housing follows the shape of detectors which is hexagonal at the front end and cylindrical at the rear side. The wall thickness of the can is 0.7 mm and the distance between the Ge crystal and the wall of the can is 0.3–0.7 mm. The circular lid of the capsule contains the feedthroughs for the high-voltage and the detector signals. In the original development the housing was hermetically sealed with the lid by electron-beam welding under vacuum. In order to operate the HPGe detector in a vacuum, the capsule is pumped through an Al tube which is closed by pinch-off. An activated getter material is mounted insight the capsule on the lid. In this way an ultra pure vacuum is maintained in the whole temperature range from the operating temperature to the annealing temperature for removing a neutron damage of the Ge crystal. The getter material inside the encapsulated crystals is designed to keep a pressure below 10^{-6} mb for a period of 40–50 years. Two international patents were granted for the development of this encapsulation technique for Ge detectors [7,8].

In case of a problem with the Ge detectors itself inside the housing the welded capsule has to be opened by machining. In some cases the capsule can be sealed by welding again, but mostly the capsule has to be replaced and the parts are lost. The encapsulated, non-segmented EUROBALL detectors have demonstrated the exceptional reliability of the novel technology. More than 90% of the 120 detectors produced for EUROBALL some 30 years ago are still operational with their initial properties without any repairs and after numerous annealing of neutron damage. However, the extremely complex 36-fold segmented detectors significantly increased the need for repairs. This motivated the development of an improved technique and to overcome the disadvantages caused by the repetitive cycles to get all the individual signals working. Pictures of the welded Miniball and AGATA capsule are shown in Fig. 1.

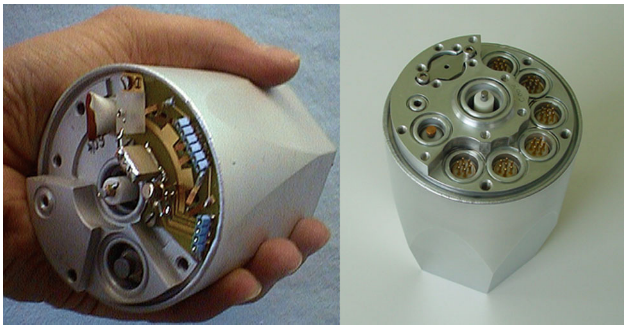

Fig. 1 The encapsulated Miniball detector (six-fold segmented) (left) and the AGATA detector (thirty six-fold segmented, three different shapes) (right) are shown. The housing of the HPGe detectors was hermetically sealed by electron-beam welding under vacuum

3 New encapsulation technique

In the design of a reusable capsule for HPGe detectors a reliable sealing technique is critical to ensuring optimal performance and longevity. The HPGe detector operates within a temperature range that can span 300°, requiring a seal that can withstand thermal expansion and contraction without compromising the integrity of the capsule or the detector. The new seal should allow for repeated assembly and disassembly without significant degradation. Several sealing solutions have been traditionally considered for this purpose, including copper, aluminium, and indium seals. However, each of these materials presents challenges, particularly when it comes to damage the aluminium capsule and lid, as well as ensuring repeatability in sealing performance.

Copper seals are commonly used due to their excellent thermal conductivity and ability to maintain a strong, hermetic seal under a wide range of temperatures. However, when used with aluminium components, copper seals can lead to galling or damage to the softer aluminium surfaces of the capsule flange and lid. The high mechanical forces exerted during tightening or temperature cycling can cause indentations, leading to a loss of seal integrity over time. Furthermore, copper seals can undergo deformation or cracking after repeated use, making them less ideal for applications requiring a reusable, durable solution. Aluminium seals are another viable option, offering good compatibility with aluminium capsule components. While aluminium is softer than copper, its lower strength limits its ability to maintain a strong seal under extreme temperature variations. The repeated thermal cycling associated with HPGe detector operation can also cause the aluminium seal to deform, leading to leaks and failure of the seal. Additionally, like copper, aluminum seals can also damage the aluminium flange and lid through friction and deformation, especially after multiple cycles of assembly and disassembly. Indium seals are often favoured for their malleability and ability to form a tight seal under low pressures. Indium can conform well to irregular surfaces and create a vacuum-tight seal without the need for excessive force. However, indium has its drawbacks when used in a reusable context. The malleability of indium leads to potential creep and deformation over time, especially when exposed to the high temperature cycles typical in HPGe detector operation.

To address the limitations of traditional sealing methods, a promising new solution involves the use of a metal-elastic seal. The principle behind this type of seal is based on a coiled spring mechanism, where the spring is covered with an aluminium alloy that is softer than the capsule flange. The metal-elastic seal offers a more reliable and durable sealing solution for reusable HPGe detector capsules. The coiled spring provides a consistent, elastic force that compensates for thermal expansion and contraction across the wide temperature range, ensuring that the seal maintains its integrity without permanent deformation. The aluminium alloy covering the coiled spring is selected to be softer than the capsule flange and lid, preventing damage to the delicate aluminium surfaces while still providing a strong, hermetic seal. This design offers the flexibility to be repeatedly installed and removed without causing wear on the sealing surfaces, which significantly enhances the lifespan and usability of the capsule. The metal-elastic seal's design is particularly advantageous for applications that require frequent maintenance or repairs, as it can be reused multiple times without compromising the sealing effectiveness. This solution minimizes the mechanical stresses typically associated with traditional seals, ensuring the protection of both the HPGe detector and the capsule components. Furthermore, the metal-elastic seal can be tailored to provide optimal sealing performance across a wide range of environmental conditions, making it a robust and reliable choice for HPGe detector capsules. For details of the employed metal-elastic seal see [9].

3.1 Mechanical design

This section describes the mechanical set-up with the new encapsulation technology for the detectors of the Miniball and the AGATA spectrometer. The drawings for the Miniball and the AGATA capsule are shown in Fig. 2. Due to the varying shapes and sizes of the Miniball and AGATA HPGe crystals, a single design solution would not suffice. The geometries of the crystals differ in both size and symmetry (Miniball symmetric, AGATA asymmetric), necessitating the creation of separate designs tailored to each crystal's specific requirements.

To maintain compatibility with the existing experimental set-up, the new designs had to integrate seamlessly with the pre-existing mechanical framework, particularly the cryostat's holding structure. The cryostat's outer envelope, which houses the HPGe detectors and maintains the necessary cryogenic environment, was a key component that had to remain

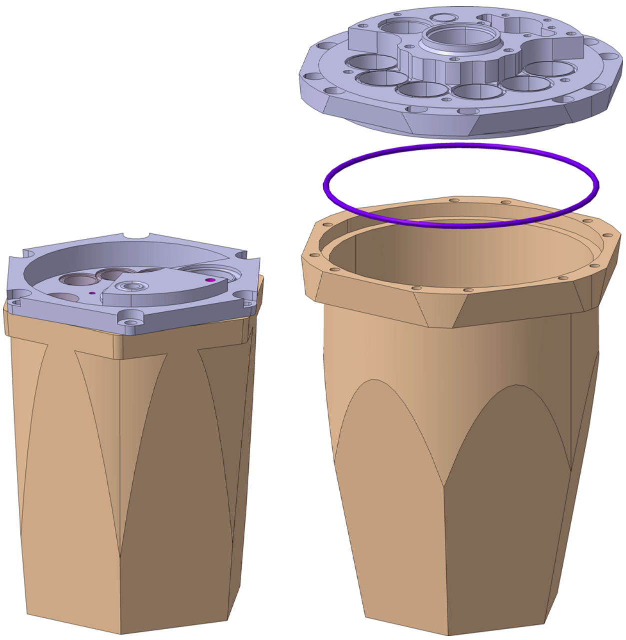

Fig. 2 Different designs with the new encapsulation are realized for the Miniball (left side) and the AGATA (right side) Ge crystals. The semi-hexagonal tapered Miniball Ge detector has a hexagonal front face, a circular shape at the rear side with a diameter of 70 mm, the length of the Ge crystal is 78 mm. The tapering angle accommodates for a target to detector distance of 43 cm. The tapered AGATA Ge detector has an irregular hexagonal front face, a circular shape at the rear side (diameter of 80 mm). The length of the Ge crystal is 90 mm. The tapering angle allows for a target to detector distance of 23.5 cm. The metal-elastic seal is positioned between the front part of the capsules and the lid with feed-throughs

unchanged. The challenge in developing the new encapsulation solution stemmed from the space constraints imposed by pre-existing cryostats, which had been designed for older detector systems featuring welded capsules, and by the space between the capsules around the lids (see Fig. 1). Three capsules are closely-packed in the Miniball cryostat as well as in the AGATA cryostat. Both detector types are tapered for a maximum coverage with Ge in their spherical spectrometers. The AGATA detector has a tapering angle of 10° giving enough space for a sealing rim while for the Miniball detectors the space is much more limited due to a tapering angle of 8° which allows only for six screws in the corners of the hexagonal lid. Also the limited available space within the cryostats posed a significant difficulty. The development needed to accommodate for additional radial space of the capsule for a rim, a sealing groove and a sufficient number of large screws within the tight confines of the pre-determined cryostat design. The space for the spring-loaded seal was designed with particular emphasis on its ability to maintain the necessary sealing pressure across both contact surfaces throughout the temperature extremes. To ensure a reliable and durable seal, a rim were engineered to precisely conform to the sealing surfaces. Through several empirical iterations, the screws and the sealing groove were optimized to meet the requirements for tightness, compatibility with the existing cryostats, and the accommodation of the Ge crystals and their conduits.

High requirements for the pressing force of the spring-loaded metal seal are demanded to maintain the vacuum or high-purity gas filling of the capsule during operation of the detectors within the required temperature range of about 77 K liquid nitrogen temperature and a temperature of around 105° to anneal neutron damages. The most difficult problem to overcome was that the spring-loaded seal has to be positioned onto a narrow rim on both contact surfaces, which conforms to the sealing surfaces. The ductility of the seal material is lower than the surfaces and allows to compensate for the small irregularities at the surfaces when it is compressed. The seal has to withstand enormous contact forces to the sealing surfaces that are necessary for the correct operation of the metal-elastic seal. This affects the seal, which cannot be used a second time. The forces from the side of the lid and from the side of the housing must act in opposite directions on the seal. The use of aluminium in the smallest possible amount was necessary in order not to impair the detector properties when detecting gamma radiation.

The mechanical development of an encapsulation technology that eliminates welding while maintaining sealing integrity was successfully achieved through careful design optimization. The key challenge of working within the limited space available in existing cryostats was overcome through iterative testing and refinement of the sealing groove and screw placement. The resulting encapsulation solution meets the demanding requirements of tightness, compatibility with existing infrastructure, and the ability to withstand the environmental conditions necessary for HPGe detector operation.

3.2 Ultra-high vacuum stability

One of the most critical aspects of the new capsule design for these detectors is its exceptional tightness, which ensures the maintenance of an ultra-high vacuum pressure over extended periods. The key challenge was to develop a capsule that not only maintains this vacuum integrity but also does so across a wide range of temperatures, with no degradation in vacuum properties due to temperature fluctuations. In order to illustrate the development phase results for the Miniball detectors are shown. Very similar findings were obtained for the AGATA detectors.

First, several capsules without HPGe crystals were used to evaluate their vacuum properties under ultra-high vacuum conditions at temperatures ranging from 77 K up to +105°. A common method to detect leaks is to use a leak detector; the device employed in this work was the “Pfeiffer Vacuum

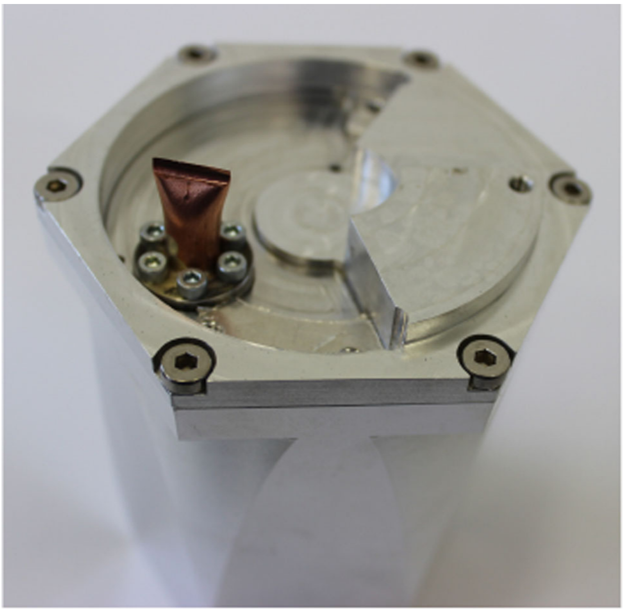

Fig. 3 Details of the Miniball capsule used for the development and test of the metal-elastic seal. The capsule is evacuated through the copper tube which is closed after filling the capsule with He by pinch-off

ASM 340". The leak detector is sensitive to a helium leak rate down to $10^{-10} mbar \cdot l/s$. The temperature of the capsules and the cryostat was measured by two PT100 resistance thermometers. To achieve the required low temperatures, the experimental set-up was cooled by liquid nitrogen, while high temperatures were achieved through a heating resistor. The test procedure started by filling the capsule with helium to a pressure of 800 mbar, and then sealing the copper tube tightly by compressing it with pliers, a technique known as "pinch off". This process involved inserting a copper tube on top of the capsule, filling it with He gas. After sealing, the helium-filled capsule was placed inside a second, larger vacuum vessel that was part of the detector cryostat system. The capsule was connected to the cryostat's dewar vessel using a copper cold finger, enabling efficient thermal contact. A heating resistor was used to regulate the temperature of the capsule above room temperature. A picture of the capsule used in the development phase can be seen in Fig. 3.

The vacuum properties and tightness of the sealed capsules were monitored during numerous test runs. An entire test run consists of leak detection measurement at room temperature, subsequent cooling to nitrogen temperature and the subsequent warming up and heating to +105°. The measured values of two complete runs are shown as examples in Fig. 4. The resistance of the two PT100 decreases very fast during the cooling phase, when the cryostat dewar vessel was filled with liquid nitrogen and the temperature of the capsule dropped rapidly. The typical cooling down time from room temperature to below 80 K takes less than one hour (see Fig. 4). Special attention was paid to the phases

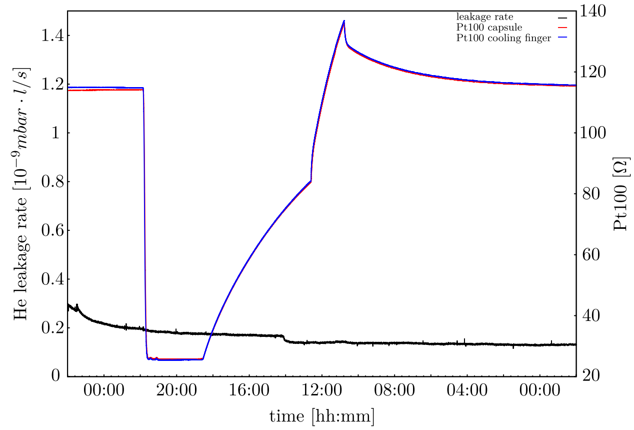

Fig. 4 The plot shows the leak rate (in black), the two resistance values of the PT100 at the cooling finger (in blue) and at the capsule (in red) as function of measuring time. An entire test run consisting of leak detection measurement at room temperature, subsequent cooling to nitrogen temperature and heating up to +105°. The electrical PT100 resistance values of 20Ω to 140Ω correspond to a temperature range of 77 K to +105°

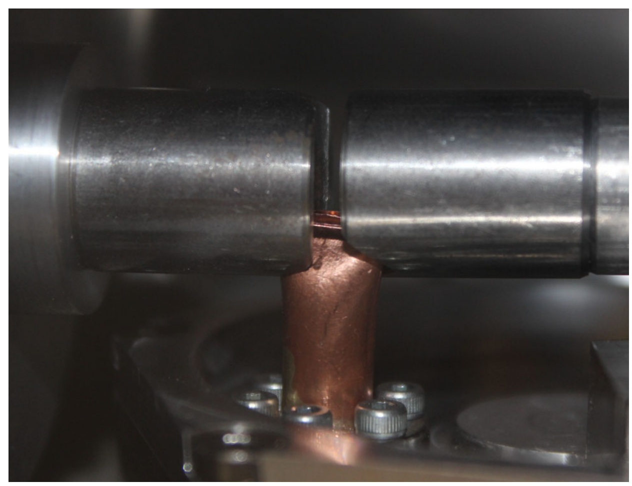

Fig. 5 Clamp for opening the unpinned copper pipe that can be pushed together via an externally accessible handwheel to open the closure of the copper tube

of significant temperature changes, as these are expected to induce mechanical contraction or elongation of materials, potentially leading to vacuum leaks.

At the end of each test series it was proven that the helium gas had not been pumped out through a leak before the leak tester was operational. For this purpose the capsule was mounted in a special vacuum chamber which allowed to create a leak at the copper tube by compressing it between two steel rods. The arrangement is shown in Fig. 5. The outcoming He was then detected by the leak tester.

For a final evaluation of the leak rates achieved, further measurements were carried out in order to determine contributions from the cryostat alone. For this purpose, several leak test of the cryostat without the capsule installed were performed under similar conditions. The comparison between the average leak rates with and without capsule clearly shows that the measured leak rate can be explained solely by the cryostat. In summary, the results from several measurement cycles, in which the new capsules were subjected to cooling from room temperature to cryogenic temperatures and then heated back to 105°, showed no evidence of leakage. Despite the large temperature variations, the capsules demonstrated excellent vacuum tightness, with no detectable helium leaks over the entire measurement period. In summary, the new capsule design is able to maintain a stable ultra-high vacuum and it remains unaffected by the thermal stresses induced by temperature changes.

Fig. 6 The new encapsulation of the Miniball and AGATA HPGe detector is based on a metal-elastic seal between the capsule lid and the crystal container. A seal of the AGATA detector is shown between the two detectors. The delicate crystals can now be accessed in a replicable way by opening and closing the capsule in a controlled way

3.3 New detectors

The new encapsulation technique was developed using prototype capsules, along with the necessary mechanical components and equipment, at IKP Cologne. Upon successful completion of this phase, Mirion began constructing the first encapsulated HPGe detectors for the AGATA spectrometer. In the subsequent phase, the HPGe detectors for the Miniball array were also manufactured.

The three slightly different types of AGATA detectors, each with 36 segments and irregular shapes, are more demanding and complex compared to many other detector designs. In contrast, Miniball detectors consist of only six segments and have a regular sixfold symmetric shape. The new encapsulation technique presented additional challenges when applied to Miniball detectors due to their smaller size at the cylindrical end and the limited space available for the new metal elastic seal. Unlike the AGATA detectors, the rim for the seal and the spacing for the screws were more confined. Furthermore, the number of screws was restricted to six, positioned at the corners of a hexagon, adding tight restrictions to the design and assembly process. Pictures of the reusable housing and lid for the Miniball and the AGATA detectors are shown in Fig. 6.

The following paragraph presents the final results achieved for the AGATA detectors. A meaningful comparison is made between 40 detectors manufactured using the previous electron welding technique and 30 detectors featuring the new metal elastic seal, all of which are currently in operation. Additionally, results are available following the full assembly of the AGATA cluster systems, which integrate three different detector shapes within a single cryostat.

The final assembly of such a system is depicted in Fig. 7. The installation of the three capsules has been made more straightforward due to the enhanced mechanical repeatability of the critical interfaces between the cooling system of the cryostat and the outer surface of the capsule.

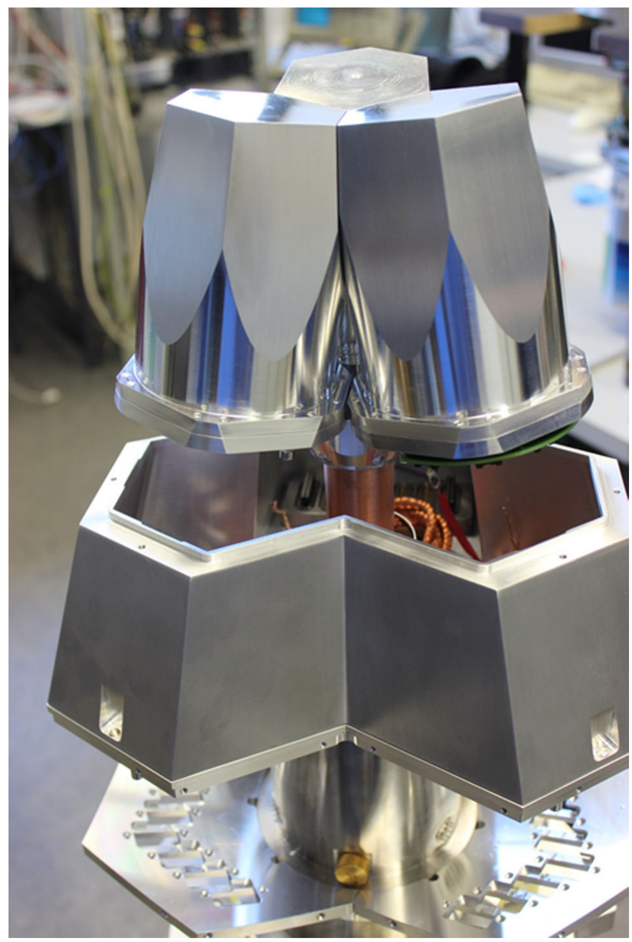

Fig. 7 AGATA triple cluster detector comprising three differently irregularly shaped HPGe detectors manufactured with the new encapsulation technique

3.4 Detector performance

The new encapsulation technology was used for the production of new HPGe detectors for the AGATA spectrometer and the Miniball spectrometer after the development phase was completed. Meanwhile, 40 AGATA detectors with the old encapsulation technique and 30 of these detectors with the new metal-elastic seal have been supplied by Mirion. A comparison between the two groups of detectors shows no significant differences and both type of detectors meet the specifications for energy resolution perfectly, as shown in Fig. 8. The energy resolution is well below the following specification values: The energy resolution (FWHM) of the core contacts is ≤ 2.35 keV for E_γ= 1.33 MeV and ≤ 1.35 keV for E_γ= 122 keV. For the 36 segments, the resolution (FWHM) is ≤ 2.30 keV at 1.33 MeV (with a mean value of ≤ 2.1 keV) and ≤ 1.3 keV at 60 keV (with a mean value of ≤ 1.20 keV). Since the low energy resolution values are dominated by electronic noise, the obtained results demonstrate the successful integration of the new encapsulation technique into the existing signal readout scheme.

The average energy resolution values of AGATA HPGe detectors with the old (welded) and new (metal seal) encapsulation technology are compared in Table. 1. The energy resolution values (FWHM) are given for a γ-ray energy of 60 keV (^{241}Am) and of 1.332 MeV (^{60}Co). A comparison between 40 detectors with the old encapsulation technique and the new technique shows in all four cases a clear improvement of the average energy resolution values. At low energies the average of the segment values are measured to be 1075 eV and 1028 eV, while the average of the core values amounts to 1.229 keV and 1.095 keV at the same energy. For the 1.332 MeV (^{60}Co) γ-ray energy, the average energy resolution of all segments is 2.057 keV and 2.004 keV and while the core energy resolution is 2.241 keV and 2.133 keV (see Fig. 8).

The new improved mean values from detectors with new encapsulation cannot be only attributed to the new sealing technique. Other changes along the Ge crystal production line, deepened experience of the manufacturers, refined electronic could have caused the better energy resolution values. However, the new encapsulation technique is fully compatible with the initial development. The many years of development and continuous improvement of the AGATA detectors and cryostats by the detector manufacturer Mirion and the cryostat manufacturer CTT have probably contributed to the successful transition to the new detectors after the first 40 detectors. Especially, the AGATA HPGe detectors with the new metal-elastic seal have operated well within the specification for the energy resolution. In addition, the final assembly of the individual detectors in the cryostats has been simplified as expected, as the irregularities caused by the electron beam welding have been eliminated.

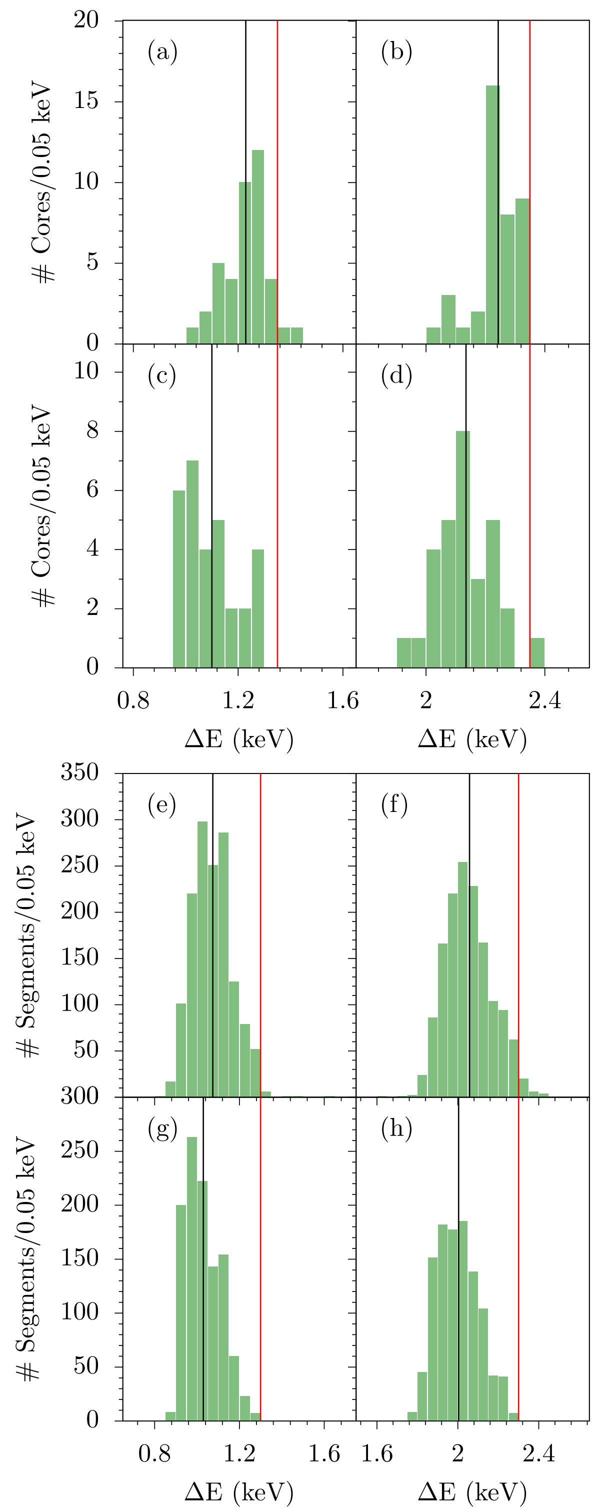

Fig. 8 Summary of energy resolution values (FWHM) (**a**, **b**) of 40 core signals manufactured with welded capsules and **c**, **d** 30 core signals of AGATA HPGe detectors with the new encapsulation technology; **e**, **f** of 1440 segment signals from 40 welded capsules and **g**, **h** 1080 segment signals from 30 AGATA detectors (new encapsulation). The energy resolution values are given for a γ-ray energy of 60 keV (^{241}Am) (**a**, **c**, **e**, **g**) and of 1.332 MeV (^{60}Co) (**b**, **d**, **f**, **h**). The AGATA energy specification limits for both γ-ray energies are included as red lines. The mean values of the energy resolution are given as black lines

Table 1 Energy resolution values (FWHM) for different energies of 60 keV (^{241}Am) and of 1.332 MeV (^{60}Co) determined for core energy signals and segments signals of 40 AGATA HPGe detectors based on the old (welded) and of 30 detectors based on the new (sealed) encapsulation technology . The eight values are also indicated in Fig. 8

Energy	Core	Core	Segments	Segments
	Welded	Metal seal	Welded	Metal seal
[keV]	FWHM [keV]			
60	1.229	1.095	1.075	1.028
1.332	2.241	2.133	2.057	2.004

4 Conclusion

In conclusion, the new capsule design successfully meets the demanding requirements for vacuum tightness and stability under varying temperature conditions. The successful implementation of this design, tested through rigorous empirical validation, ensures that the detectors will maintain the necessary ultra-high vacuum over extended periods without compromising their performance, even in the phase of significant temperature fluctuations. This development marks an important advancement in encapsulation technology for detectors used in basic physics research, enabling long-term, stable operation under challenging experimental conditions. A patent was granted for this improvement [10].

The development of position-sensitive, encapsulated Ge detectors represents a new quality in high-resolution γ-ray spectroscopy. The encapsulation technology improved the reliability of Ge detectors and their annealing of radiation damage considerably, such that for more than 20 years this technology is applied in many space missions with HPGe detectors. Furthermore Compton-cameras with position-sensitive HPGe detectors have an interesting potential for application of imaging methods in medicine, nuclear waste disposal and homeland security.

Acknowledgements The authors J.E., H.H., P.R. and S.T. acknowledge an ongoing fruitful and constructive cooperation with the company Mirion Technologies (Canberra) France SAS. The authors thank H.-G. Thomas (CTT, Montabaur) for providing Fig. 7 of the AGATA triple cluster.

Funding Open Access funding enabled and organized by Projekt DEAL.

Data Availability Statement Data will be made available on reasonable request. [Author's comment: The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.]

Code Availability Statement Code/software will be made available on reasonable request. [Author's comment: The code/software generated during and/or analysed during the current study is available from the corresponding author on reasonable request.]

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