## 10. The technical merits of EUROBALL*

***Abstract***

*The EUROBALL project is an outstanding scientific and technical success. This contribution summarises the technical achievements of the project. These include the development of state-of-the-art radiation detectors and associated electronics and data acquisition systems. These developments have resulted in a spectrometer with an unprecedented level of sensitivity enabling the atomic nucleus to be studied at the extremes of angular momentum, deformation, isospin and temperature.*

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## 10.1. Introduction

EUROBALL represented the next phase in the development of large gamma-ray arrays in Europe [1]. It was an amalgamation of all the technical developments made in several European array projects. These arrays with their very high efficiency and excellent peak to background ratio led to a revolution in the mid 1980's in nuclear spectroscopy [281] with the discovery of many new nuclear structure phenomena.

Gamma-ray detector arrays consist of as many as possible high-resolution Ge detectors around the reaction centre. A scintillation detector to detect and reject the scattered radiation from the germanium crystal surrounds each of the Ge detectors. These escape-suppressed spectrometers (ESS) improve the signal to noise of the Ge spectra, which is quantified by the peak to total ratio PT. A typical ESS is shown in Figure 10.1. For $^{60}$Co the PT can increase from ~ 25% to typically 65% with suppression. This improvement in the peak-to-total ratio (PT) is crucial in high fold (F) coincidence spectroscopy since the photopeak-photopeak coincidence probability is proportional to $(PT)^F$. This results in an improvement factor of > 8 in a doubles $\gamma^2$ experiment, when compared with the background, a factor of 21 for triples $\gamma^3$, 57 for quadruples $\gamma^4$ and 157 for quintuples $\gamma^5$.

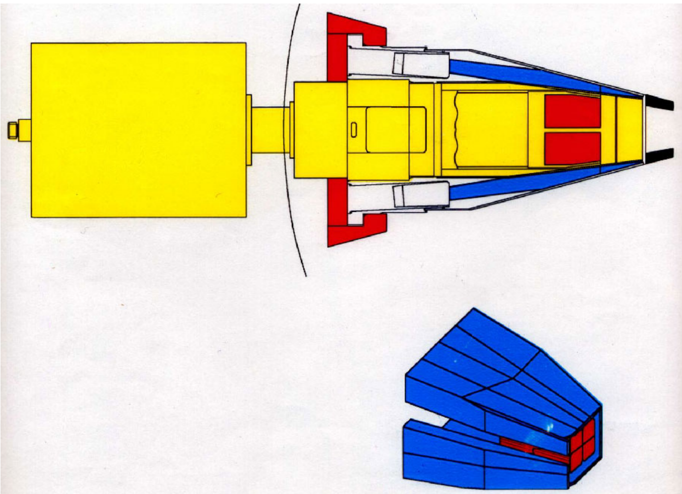

***Figure 10.1:*** *A schematic diagram of a modern escape suppressed spectrometer. The figure shows a Clover Ge detector of the EUROBALL array inside its BGO escape suppression shield consisting of 16 individual crystals.*

By the mid 1980's, arrays with ~20 ESS's having total peak efficiencies $\varepsilon_p$ of 0.5-1.0% at 1.3 MeV were constructed. These arrays included TESSA3 (UK) [282], Chateau de Cristal (France) [283], Osiris (Germany) [284], Nordball (Denmark) [285], Hera (USA) [286], and the 8π spectrometer (Canada) [287]. These arrays enabled the study of nuclear structure features that occur at an intensity of ~ 1% of the total intensity in the nucleus, see Figure 10.2 where the intensity distribution for selected high-spin phenomena is plotted.

There then followed the construction of much bigger arrays [288, 289] using large volume Ge detectors namely EUROGAM [3], GASP [2] and GAMMASPHERE [290] which lowered the observation limit by a further ~ 2 orders of magnitude.

The European arrays, GASP and EUROGAM were the first phase of the EUROBALL project. The second phase of EUROBALL was the development of composite Ge detectors, namely Clovers and Clusters. The third phase, EUROBALL III, pulled together all these developments and resulted in an array with 239 individual Ge elements with a total photopeak efficiency of $\varepsilon_p$ of ~ 10%. This allowed the unprecedented study of the properties of the atomic nucleus with a sensitivity up to or better than $10^{-5}$ of the production cross-section. As an example one can take the spectrum of a normally deformed nucleus, $^{162}$Er, to spin 60ħ [136] that has already been shown in Figure 5.1 (cf. Section 5). EUROBALL IV, which commenced operation in 1999 at IReS involved further enhancements to the project, most notably the INNER BALL spectrometer. Figure 10.2 summarises the spectroscopic sensitivity of arrays as a function of spin and the approximate timescale.

In parallel with these advances in detector technology, the electronics and data acquisition systems were also revolutionised with the building of the high compact VXI electronics and associated acquisition system.

This contribution will concentrate on the developments made in detector technology, electronics and data acquisition. I will not discuss the many ancillary detectors, that have been coupled to EUROBALL for specific experiments and have contributed greatly to the spectrometers success. They are described in detail in the following chapter and in the the EUROBALL Ancillary detector handbook [291].

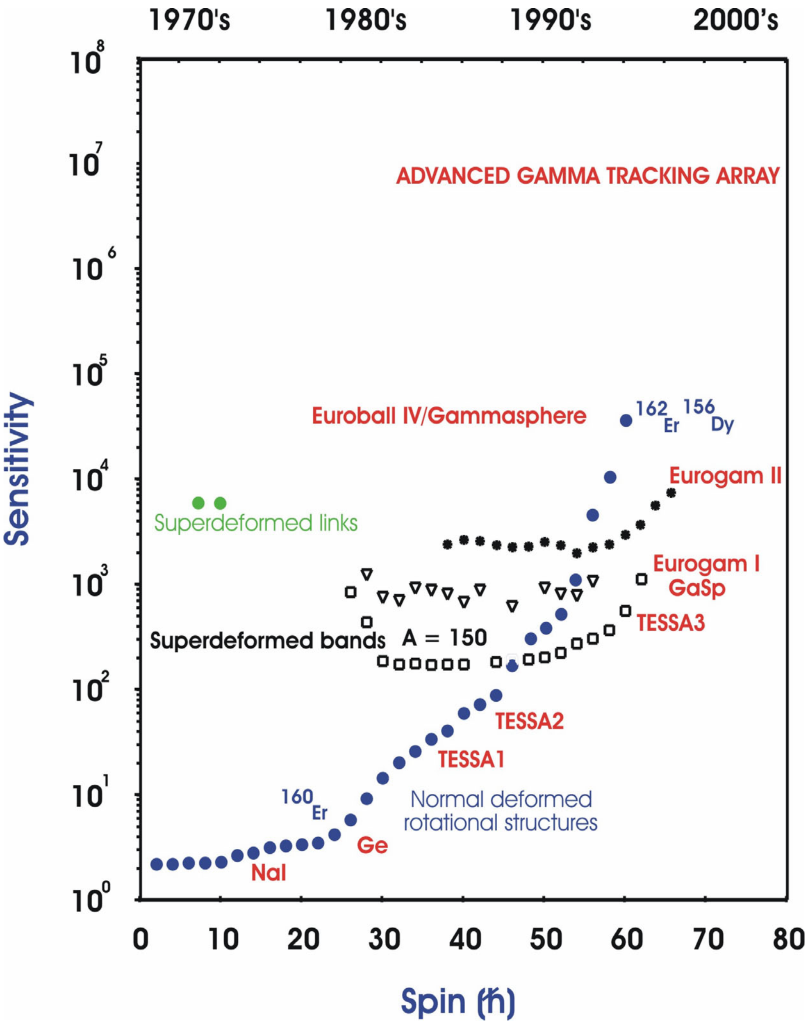


***Figure 10.2:*** *Plot of the spectroscopic sensitivity as a function of spin for various arrays. The TESSA 1, 2 & 3 arrays consisted of 4, 6 and 16 ESS, respectively [282]. The intensity distribution for selected high-spin phenomena is plotted. Normal deformed states up to spin ~ 50ħ in $^{160}$Er [288] and spin 60ħ in $^{156}$Dy [289] (•), the yrast superdeformed band in $^{152}$Dy (□) [13] and excited superdeformed bands in $^{151}$Tb (▽) [15] and $^{152}$Dy (•) [290]. The links between the superdeformed bands and the normal deformed structures in the mass A = 190 region are also shown (•).*

## 10.2. Large volume Germanium detectors

Throughout the period of the EUROBALL project the size and quality of hyperpure Ge crystals has increased. The drive for bigger and bigger detectors was given by the nuclear structure community because of the need for higher and higher detection efficiency. Today HPGe crystals up to with relative efficiency of up to 200% are available.


***Figure 10.3:*** *The growth of Germanium crystals;*

EUROGAM (Figure 10.4) and GASP (Figure 10.5) were the first large detector arrays to use 65%-85% relative efficiency germanium detectors. This built on the experience gained in France where 12 similar large detectors had been used in the Chateau de Cristal [283].

EUROGAM I used 45 detectors in bismuth germanate (BGO) suppression shields and had a total photopeak efficiency of 4.5% for 1.33 MeV gamma rays. The GASP array has 40 ESS's and can be operated in two modes, one with an efficiency of 6% and one with a lower efficiency but with the addition of an inner BGO ball. These detectors are used in the forward section of EUROBALL which contains 30 ESS's. They are arranged in three rings around the beam direction with the Ge crystals 375 mm from the target and have a total efficiency of $\varepsilon_p$ ~1.2%.

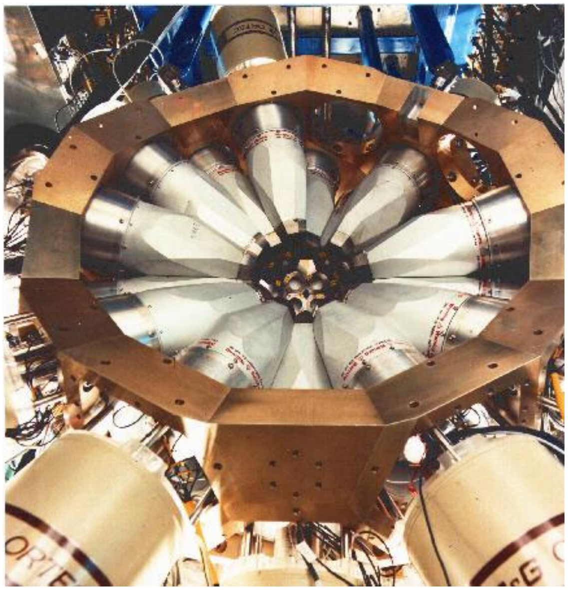

***Figure 10.4:*** *The EUROGAM I spectrometer.*

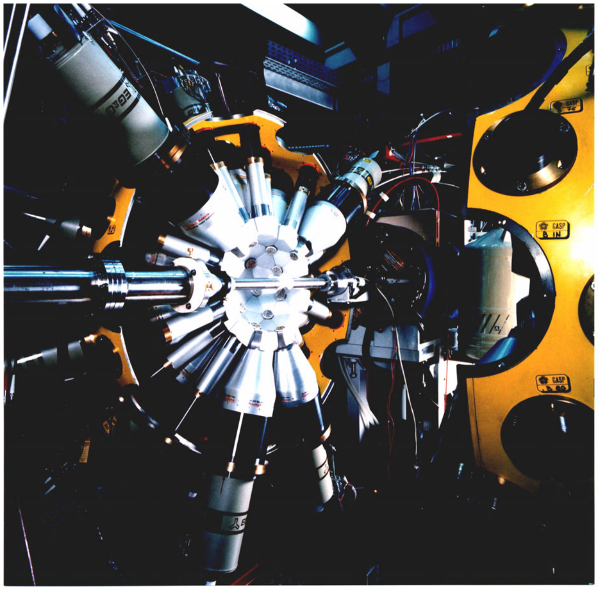

***Figure 10.5:*** *The GASP spectrometer*

## 10.3. Composite Germanium detectors

The total photopeak efficiency that can be obtained using an array of single crystal detectors (as in EUROGAM I and GASP) is limited by the size of the crystals and by the cost. Indeed, the maximum efficiency that can be obtained using detectors of 80% relative efficiency is ~ 10% [292]. In addition, even though these large Ge detectors may be packed close to the target to give a large total photopeak efficiency, the spectrum quality is poor due to Doppler broadening. Ideally, large detectors with high granularity are needed. Developments in Ge detector technology sought to achieve this with the development of composite detectors.

A composite detector contains several Ge crystals packed closely together in the same cryostat. The signals from each crystal are added together, including signals caused by scattering between two or more adjacent crystals. In this way a large detector can be created which has a very high photopeak efficiency and a high resolving power, since the small individual crystals minimise the effect of Doppler broadening. An array of such detectors has high granularity and high efficiency. Indeed a full $4\pi$ array of Cluster detectors, see below, can have an efficiency $\varepsilon_p$ of over 20%.

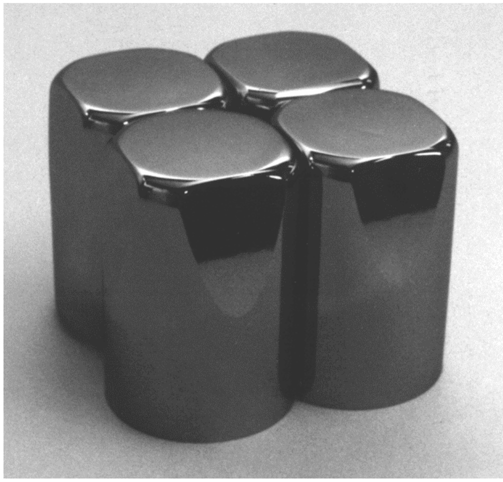

***Figure 10.6:*** *The Ge crystals as arranged in a Clover detector*

The first composite detector to be used in a large array (EUROGAM II) was the Clover detector. This detector consists of four coaxial n-type Ge crystals arranged in the configuration of a "four-leaf Clover" and housed in the same cryostat (see Figure 10.6).

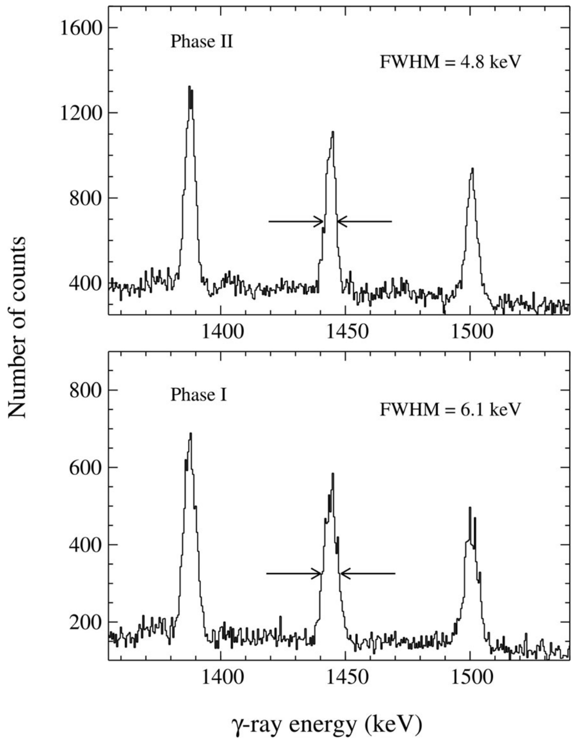


***Figure 10.7:*** *Spectrum for* $^{149}$*Gd obtained using the reaction* $^{30}$*Si +* $^{124}$*Sn at* $E_{beam}$ *= 158 MeV,* $\beta$ *=2.1%, in EUROGAM I and II. The improved resolution for EUROGAM II for the* $E_\gamma$ *= 1450 keV transition as a result of the use of the Clovers is clearly demonstrated.*

The Clover detector [293] was developed in collaboration between CRN-Strasbourg and the company Eurysis Mesures. Each crystal is ~50 mm in diameter and ~ 70 mm long, before being shaped at the front to optimise the packing. The relative efficiency of the Clover detector is 140% when the scattered events are included. In EUROBALL, as in EUROGAM II, the Clover detectors are in the central section where the Doppler improvement effects are the greatest. They are arranged in two rings each with 13 detectors covering roughly 2π of solid angle. The total $\varepsilon_p$ for the 26 Clovers is 3.8%. Figure 10.7 demonstrates this improvement in the spectroscopy of superdeformation in $^{149}$Gd using the same reaction in EUROGAM I and II .

The Cluster detector [294] consists of seven close packed tapered hexagonal Ge crystals (70 mm diameter and 78 mm long before shaping), each of relative efficiency 60% and resolution ~ 2 keV at 1333 keV, housed in a common cryostat (see Figs. 10.8 and 10.9). In order to achieve the very close packing required, the technique of encapsulating the crystals was developed as a collaboration between KFA Jülich, the University of Köln and the company Eurysis Mesures. Encapsulation decouples the crystal and cryostat

***Figure 10.8:*** *The encapsulated Ge crystal for the EUROBALL Cluster detector.*

vacuum by housing the crystal in a thin walled (0.7 mm thick), sealed aluminium capsule. The crystal is sealed for life thus avoiding the problems of surface contamination, a problem common in standard detectors. Encapsulation has proven to enhance the reliability of Ge detectors considerably. The failure rate of the 122 encapsulated EUROBALL detectors produced since 1993 is less than 4 %. After neutron damage all detectors have been annealed several times in the users lab and without any failure. Encapsulation will help to preserve the properties of the detectors over many years. In encapsulated detectors the cold parts of the preamplifiers are in a vacuum separate from that of the cryostat. It has turned out that the position of the cold electronic components, the shielding between the components and the wiring is crucial to prevent oscillation of the preamplifiers and cross talk between segments. Usually, the cryostat has to be opened several times before a perfect performance of the detector system is achieved. This procedure and also the repairs of the electronics can only be performed on systems with encapsulated detectors without running the risk of damaging the Ge detectors.

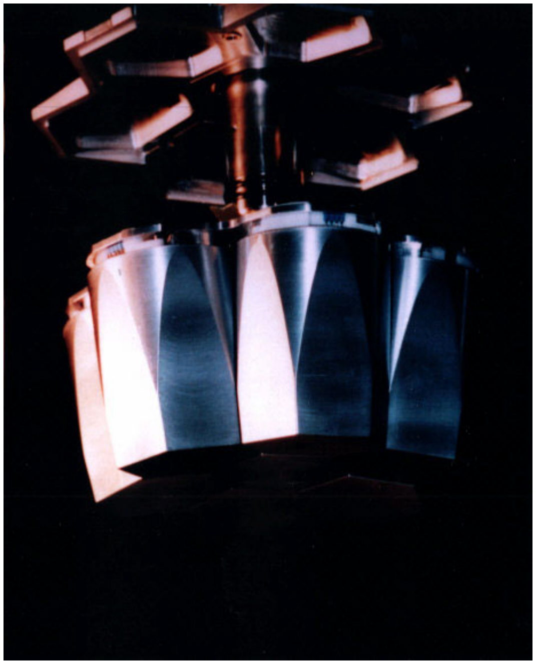

***Figure 10.9:*** *Encapsulated Ge crystals arranged in the 7 detector cluster.*

The Cluster detectors are arranged in the backward end cap of EUROBALL in three rings with the Ge crystals 445 mm from the target. The 15 clusters have an efficiency $\varepsilon_p$ of 4.4%.

Composite Ge detectors have become the standard for many applications where high-efficiency is required. Encapsulation technology has many advantages, some of which, reliability, ease of repair and handling have resulted in their use in space missions, e.g. the Mars Odyssey [295] and INTEGRAL [296] space missions.


***Figure 10.10:*** *Mars Odyssey.*

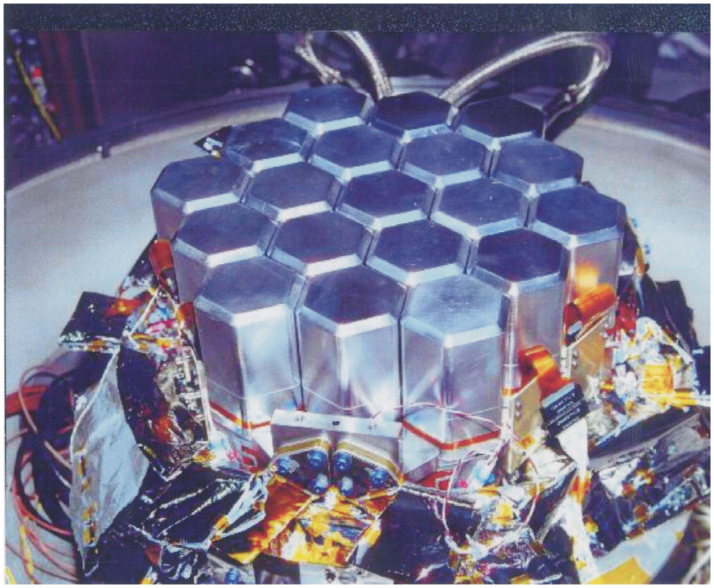

***Figure 10.11:*** *19 encapsulated detectors to be used in the INTEGRAL mission.*

## 10.4. Array design

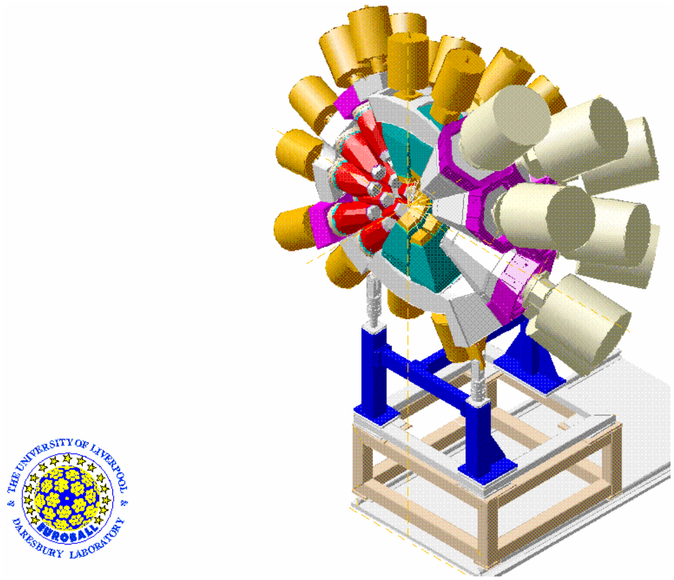


***Figure 10.12:*** *A CAD generated image of EUROBALL in design.*

***Figure 10.13:*** *The real thing, EUROBALL III in Legnaro, Italy.*

A technical achievement of EUROBALL that is often forgotten is the mechanical design itself. The array consists of three major detector types all of totally different shapes originally designed for different arrays (see Figs. 10.12 and 10.13). The design criteria included placing all the detectors together with a clearance between each adjacent suppression shield of 0.25mm, a requirement that the axis of each Ge detector looks at a common central point to an accuracy of 1mm all this with the total weight of the detectors and support structure of 9 tons. In addition to the support structure most of the detectors including the complex shaped suppression shields and their crystals were designed by the collaboration. In all the design complex three-dimensional computer aided design (CAD) systems and finite element analysis (FEA) was required.

## 10.5. Segmented Germanium detectors

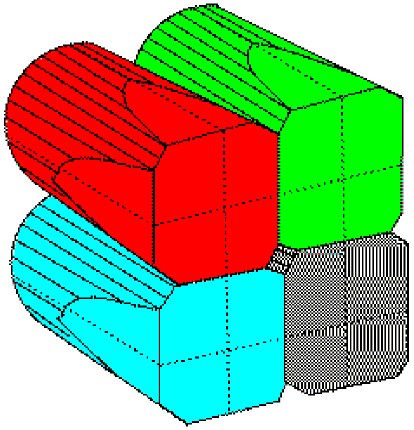

***Figure 10.14:*** *The four-fold segmented Clover detector for EXOGAM.*

Improved granularity of an array, and hence reduced Doppler broadening, can be achieved by electrically segmenting the Ge crystals. A segmented detector is a standard n-type detector with the main high-resolution energy signal taken from the centre contact and position information taken from signals on isolated outer contacts. In EUROBALL segmented Clover detectors were designed to improve the performance of the central section (see Figure 10.14). These Clover detectors have each crystal segmented into four parts producing a single detector with 16 active elements [297]. These detectors are and have been used extensively in radioactive beam experiments at Ganil, within the EXOGAM project [298], at GSI and in the SARI array at Jyväskylä. Larger crystal segmented Clovers are now being used in EXOGAM and in the VEGA spectrometer [299].

The MINIBALL array [300], currently being assembled at ISOLDE, CERN, is a prime example of the use of encapsulated, segmented detectors. MINIBALL will consist of 40 six-fold segmented, encapsulated Ge detectors. The development is based on the encapsulation technology used for the EUROBALL Cluster detector [294]. In Figure 10.15 the 6-fold segmented MINIBALL detector is shown.

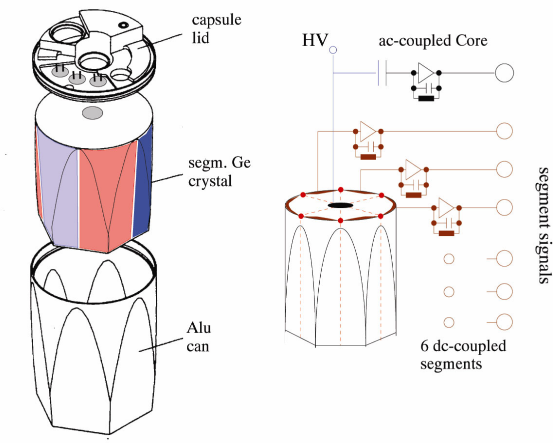


***Figure 10.15:*** *The encapsulated six-fold*

## 10.6. Electronics and data acquisition

The EUROBALL project had led to significant advances in electronics and data acquisition systems. Indeed, to the user these changes are those appearing the most dramatic. The major development has been in the compression of the electronics and software monitoring and control of the parameters. In order to achieve the degree of integration needed, the VXI (VME eXtension for Instrumentation) bus standard was used for the front-end electronics. This standard allows a large card size to be used and the mixing of both high density analogue signal processing and digital circuits. VXI cards have been built for specific applications, for example, detector signal processing, digitisation and event triggering, e.g. see [301]; VXI electronics was first used for the EUROGAM I spectrometer.

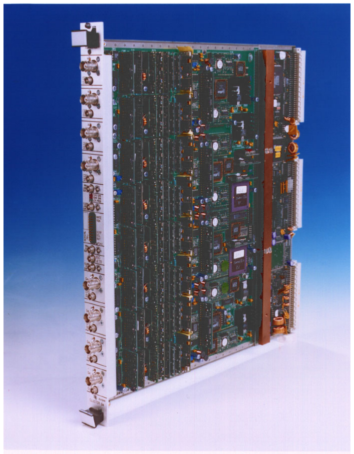

***Figure 10.16:*** *The Cluster Ge VXI card.*

The VXI electronics for EUROBALL is housed in just 9 VXI crates with additional crates for ancillary detectors. These nine crates deal with ~250 Ge channels, ~800 BGO channels and ~100 INNER BALL channels in EUROBALL IV. EUROBALL has specific VXI cards for each of its Ge and BGO suppression shield detectors. The Cluster Ge card (Fig. 10.16), for example, has 8 identical channels. Each channel has all analogue electronics for one Ge channel, including shaping and timing amplifiers, constant fraction discriminators, and analogue to digital converters to provide digitized energy, and time information. One Cluster Ge card for example, when first produced, was equivalent to eight full crates of NIM electronics.

The EUROBALL data acquisition system was designed to handle data rates up to 20 Mbytes/sec. The system comprises several components. The event collector, a VME module for each DT32/FERA bus to collect event fragments for a given number of events. These sub events are then distributed via an event builder (to construct the total event) to the processor farm via a fibre channel network. The processor farm, consisting of UNIX workstations, performs the event building and any on line analysis. Event storage will be on digital linear tapes and/or exabytes. The system is required to be able to collect the data generated by event rates up to 50 - 100 kHz in order to be suitable for a wide range of experimental situations. A more thorough overview of the data acquisition system can be found in [302].

The software to control all the different electronics modules, to provide a user interface to all parts of the system, to set-up the register in all cards, to control the spectrum and tape storage system developed for EUROBALL is called MIDAS [303]. MIDAS (Multiple Instance Data Acquisition System) is now a global standard, used in many nuclear structure laboratories and also for non nuclear structure scientific experiments.

## 10.7. EUROBALL IV and the inner BGO ball

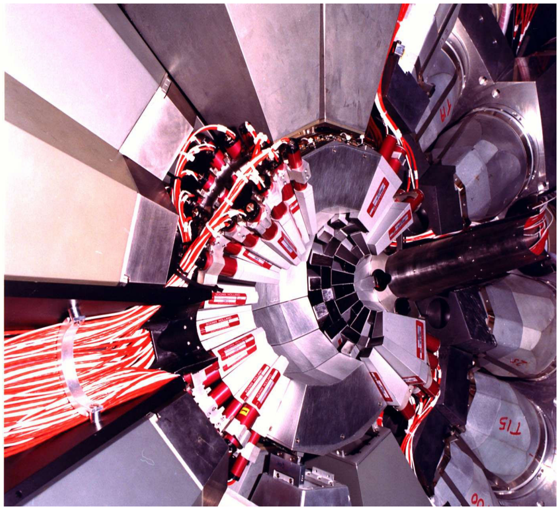

***Figure 10.17:*** *The BGO inner-ball calorimeter of EUROBALL IV.*

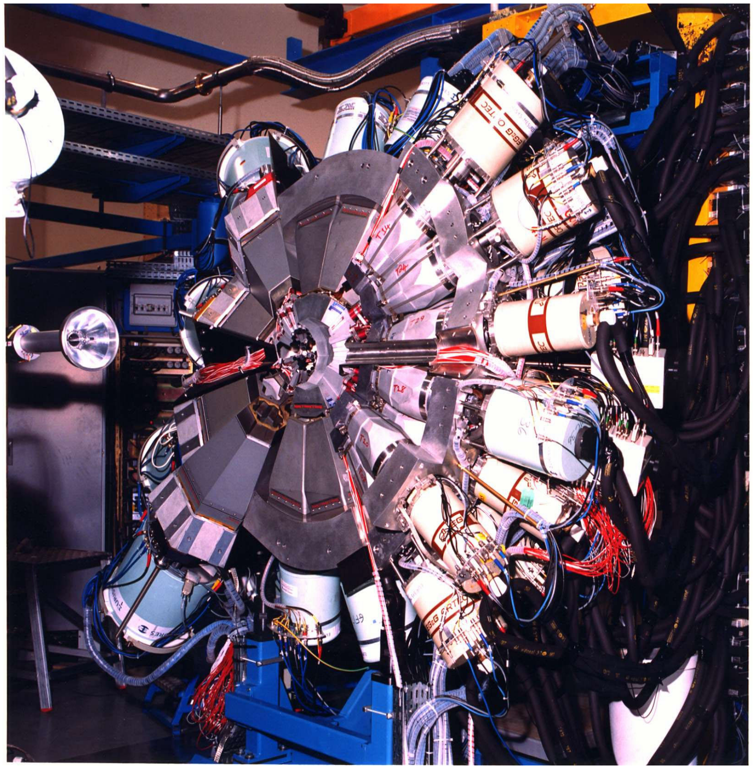

***Figure 10.18:*** *EUROBALL IV in Strasbourg, France.*

The EUROBALL spectrometer was upgraded in its second phase of operation at IReS, EUROBALL IV, with the inclusion of an INNER BALL of BGO detectors. An inner scintillator ball measures the γ multiplicity and the γ-sum energy, thus probing spin and excitation energy of a nuclear reaction. This information constitutes a highly efficient filter to select specific reaction channels and to suppress unwanted background. The INNER BALL has been designed to cover almost 4π and to have good detection efficiency. This is achieved by including the Ge detectors which cover roughly 40% of the solid angle as part of the summed energy and multiplicity measurement. The design of the INNER BALL is highly complex due to the differing shapes in the three sections of the array. In the final design the cluster section comprises 80 tapered hexagonal detectors of which there are 6 types, the central section comprises 13 detectors each containing 5 different crystals and the forward section 50 trapezoidal detectors of 5 types. The full ball, shown in Figure 10.17 is operated as a 164 element device, 59 elements from the INNER BALL and 105 elements from the Ge detectors.

The INNER BALL installed in EUROBALL IV (Figure 10.18) has proved to be a powerful addition to the spectrometer and several beautiful results from its use are shown in this report. Figure 10.19 shows the INNER BALL response from an experiment to study the very high spin states in Er nuclei.

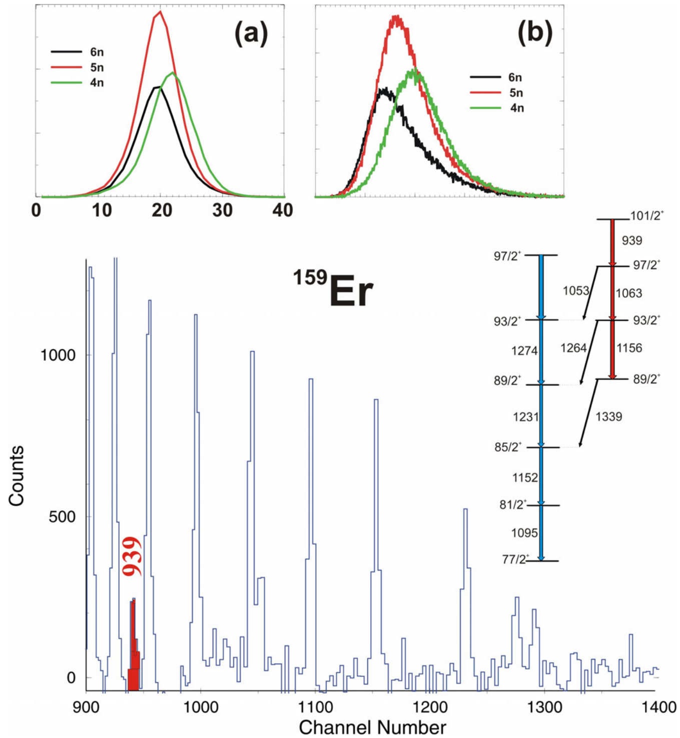


***Figure 10.19:*** *Example of the use of the inner ball. The top spectra show the (a) fold and (b) summed energy response for the 4n, 5n and 6n channels following the reaction $^{34}S$ + $^{130}Te$ at 170 MeV. The spectrum shows the yrast (+,+1/2) band in $^{159}Er$ (4n channel) established to the fully aligned band termination state at $101/2^+$.*

## 10.8. Gamma-ray tracking

The developments of large volume, segmented, encapsulated detectors and high performance and compact electronics systems, mostly through EUROBALL related collaborations has made it feasible to propose the next generation gamma-ray spectrometer based on gamma-ray tracking [304]. The sensitivity and selectivity of AGATA, the proposed project to build a 4π Ge shell [305], will make it superior to any existing spectrometer by several orders of magnitude. The project will build on the strong European collaborations established during the EUROBALL years. The realisation of AGATA will ensure an exciting and interesting future for nuclear spectroscopists in their investigation of the fascinating structure of the nucleus.

## Acknowledgements

The realisation and successful operation of EUROBALL is the result of a great deal of hard work by many people in many laboratories across Europe. All of these people should be very proud. I wish to thank several people who have given me material for this contribution, in particular, Juergen Eberth, Marie-Odile Lampert (Eurysis Mesures), Ian Lazarus, Stein Ødegård, Faisal Azaiez, Heinz-George Thomas and Pat Sangsingkeow (Ortec).