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EUROGAM, A NEW GAMMA MULTIDETECTOR ARRAY: RESULTS AND PERSPECTIVES

N. Redon

Institut de Physique Nucléaire de Lyon, IN2P3-CNRS
Université C. Bernard Lyon-1
F-69622 Villeurbanne Cedex, France

and the EUROGAM collaboration

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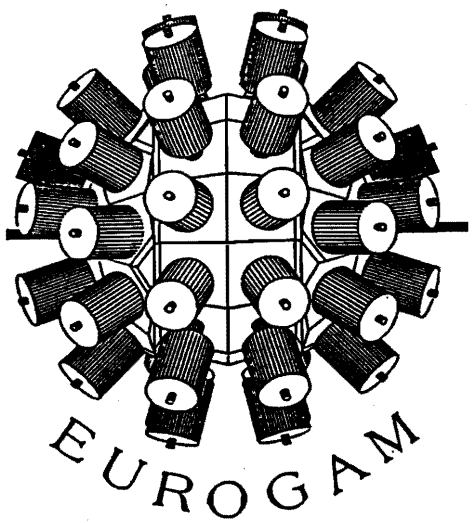

FRANCE - UK
Collaboration

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1. Introduction

The most powerfull means to study nuclear structure under extreme conditions is γ - ray spectroscopy. During the last years, the development of large arrays of escape suppressed spectrometers has revolutionized this field resulting in a greater understanding of the nuclear matter at extremely high spin. Some years ago, this field made use of a few germanium (Ge) detectors in coincidence with multiplicity filters or sum spectrometers to select events associated to the decay of a nucleus with very high spin. With these devices, the identification and resolution of γ - ray peaks associated with a fraction of the reaction channel as the order of some percents have been possible, which meant significant progress in nuclear spectroscopy. But it soon appeared that larger systems would extend the range of the spectroscopic studies. Consequently, using more Ge detectors and BGO anti-compton shields, the 1980's generation of multidetector arrays has been built in different countries : TESSA3 in the United Kingdom, CHATEAU DE CRISTAL in France, OSIRIS in Germany, 8π in Canada, HERA (Berkeley), SPIN SPECTROMETER (Oak Ridge) and MULTISPECTROMETER (Argonne) in U.S.A., NORDBALL in Scandinavia. The detection intensity limit has been reduced to fractions of a percent. This evolution is illustrated in Figure 1 [1].

With these spectrometers, the understanding of the microscopic properties of the nucleus, especially its collective behaviour or its individual excitations, has been improved and new phenomena have been observed. The most spectacular discovery with these new arrays was the phenomenon of superdeformation at high spin. The first evidence of discrete line rotational structure with superdeformation was found in ^{152}Dy [2]

with TESSA3 at Daresbury. These superdeformed states were associated with a major to minor axis ratio for the deformed prolate nucleus of 2 to 1. The observation of a discrete γ - ray transition from spin $60\hbar$ marked a remarkable advance in the study of high spin states.

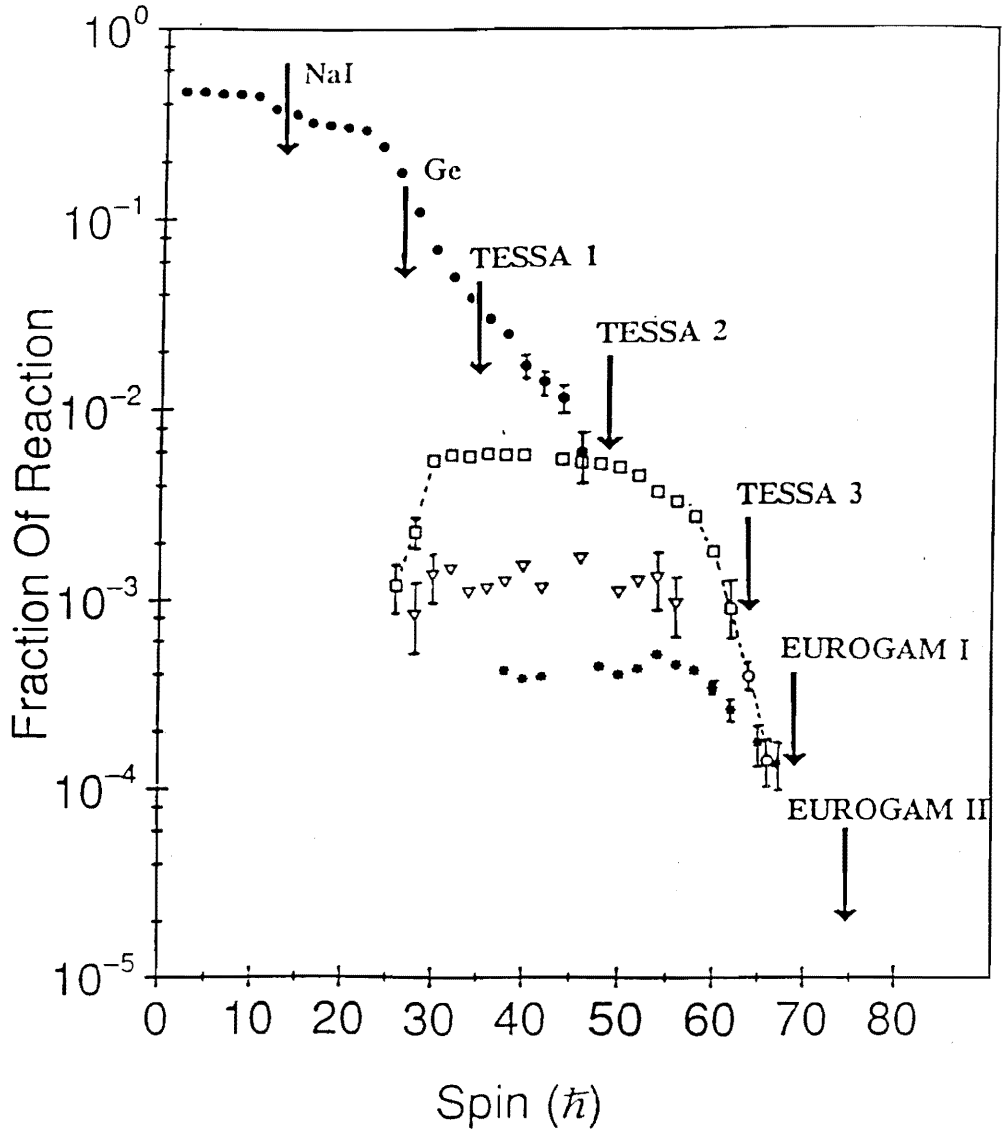

Figure 1 : *Observational limit of γ - rays. The arrows indicate the approximate observational limit of a γ - ray as a fraction of the reaction channel and the maximum observed spin for NaI detectors, smaller Ge detectors, and the arrays TESSA 1, TESSA 2, TESSA 3 and EUROGAM I, together with the prediction for EUROGAM II. The data points are as follows; solid circles (•) discrete lines in ^{160}Er measured by TESSA 2; open square (□) yrast superdeformed band in ^{152}Dy and open triangles (▽) first excited SD band in ^{151}Tb measured by TESSA 3; open circles (○) additional γ - rays in yrast SD band in ^{152}Dy and stars (∗) excited SD band in ^{152}Dy measured by EUROGAM I. [1]*

Since this first discovery, many other examples of superdeformation have been observed in the rare-earth region (A$\sim$130 and A$\sim$150) and in the A$\sim$190 mass region (see for instance the reviews [3,4]). New fascinating questions have been raised by these discoveries. The first question concerns the linking transitions between the superdeformed and the normal states via discrete or statistical γ-ray paths, for the exact experimental determination of the excitation energies and spins of superdeformed states to be compared to the mean-field theory predictions. The borders of the regions of superdeformation need to be established. The feeding of the superdeformed bands and the phenomenon of the "identical" bands are not yet understood.

Another interesting phenomenon which appeared recently is the discovery of collective oblate bands in the mass A$\sim$190 region. There is a lot of new information in that area which is developing very rapidly. These bands are populated in about the same spin range as the superdeformed bands and, like them, they were not connected to the lower-lying levels.

Major advances in our understanding of superdeformed or oblate bands and other problems in nuclear structure required a new generation of spectrometers giving improvements in sensitivity. The detection limit which was a few fractions of a percent had to be improved by two or three orders of magnitude to reach limits of 10^{-4} to 10^{-5}. For this reason, two projects, GAMMASPHERE in U.S.A. and EUROBALL in Europe have been launched.

EUROBALL started in 1992 by EUROGAM phase 1 (France - UK collaboration) at Daresbury (U.K.) [5,6] and by GA.SP (Italy) at Legnaro [6,7]. EUROGAM phase 1 and GA.SP are γ-spectrometers comprising respectively 45 and 40 tapered Ge detectors surrounded by BGO Compton suppression shields. The construction of EUROGAM has involved new and remarkable technical developments in electronics (integrated in VXI standard boards) and data acquisition techniques. EUROGAM I has been operational with the full array from October 1992 to March 1993. EUROGAM phase 2 consisting of 30 Ge tapered detectors and 24 new clover detectors is now operational near the new Vivitron accelerator at Strasbourg (France).

2. EUROGAM

EUROGAM is a french - british collaboration between ten laboratories : CENBG Bordeaux, ISN Grenoble, IPN Lyon, CSNSM Orsay, IPN Orsay, CRN Strasbourg in France and Daresbury Laboratory, University of Liverpool, University of Manchester, University of York in U.K. The phase 1 has been built at the Nuclear Structure Facility at Daresbury (U.K.) and the phase 2 at the Vivitron accelerator at Strasbourg (France).

2.1 EUROGAM phase 1

The system was composed of 45 modules consisting of a large n-type hyperpur Ge detector surrounded by a BGO escape suppression shield and placed 25 cm from the target. The detectors used have a resolution of $\sim$2.1 keV (for 1.33 MeV γ-rays) and a

photopeak efficiency of $\varepsilon_p \sim 0.23$ (relative efficiency $\sim 75\,\%$). The BGO detectors are divided into 10 optically isolated elements, each with a photomultiplier readout. The BGO is shielded from direct radiation from the target by a heavy metal collimator. With these collimators, the invidual solid angle covering by a detector is $\Omega \sim 5 \times 10^{-3}$. The system leads to a peak-to-total ratio for ^{60}Co of ~ 55-$60\,\%$ [8].

The general structure shown in Figure 2 is based on a pentagon structure including 12 pentagons surrounded by 5 counters each. In phase 1, the array was located at the target position of the Recoil Mass Separator at Daresbury then only 45 holes were filled with Ge + BGO modules since the forward part was let free for the use of the RMS.

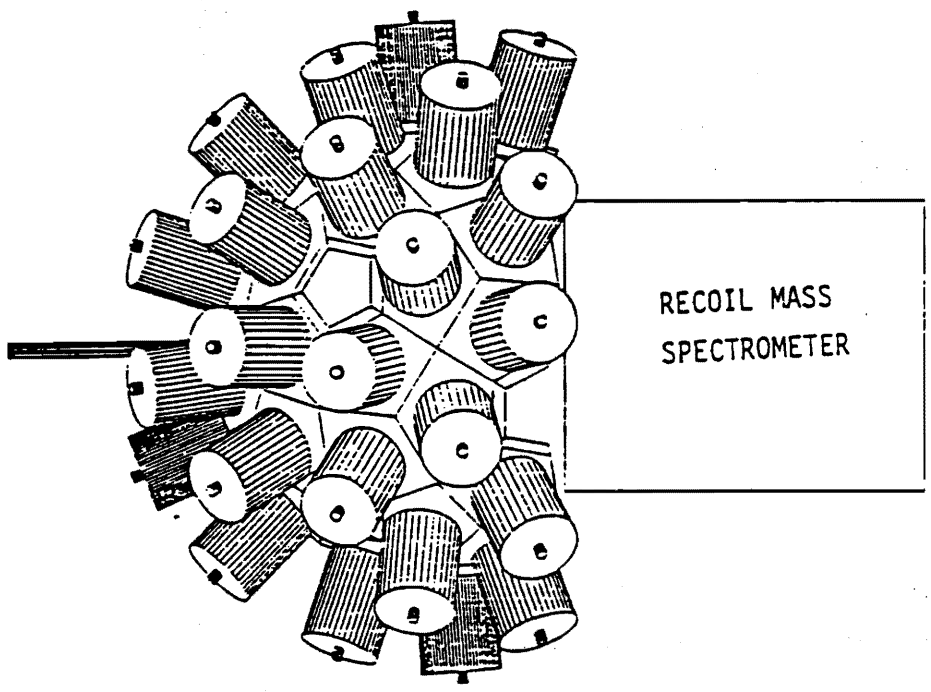

Figure 2 : *General structure for EUROGAM phase 1.*

A multidetector can be characterized by two quantities :

- the resolving power $\mathrm{R} = \frac{SE_\gamma}{\Delta E_\gamma}$ PT depending on the peak-to-total ratio PT, the resolution of γ-rays in the detector spectrum ΔE_γ and the average separation SE_γ between γ-rays in the rotational band we want to study. For EUROGAM phase 1, R was ~ 5-7 according to the experiment. The resolving power approaches the quality of the data, especially the peak-to-backgroung ratio.
- the total photopeak efficiency which has to be maximized simultaneously with the optimization of the energy resolution and the peak-to-total ratio : $\varepsilon_\mathrm{T} = N\Omega\varepsilon_p \mathrm{P}_\gamma$. For EUROGAM phase 1, we obtained a total photopeak efficiency $\varepsilon_\mathrm{T} \sim 5\,\%$.

With EUROGAM phase 1, the detection limit reached 10^{-4} (see Figure 1) and the average fold went from 2 up to 4.

2.1 EUROGAM phase 2

The large crystal diameter of the Ge detectors used for EUROGAM phase 1 introduced a larger Doppler broadening effect which implied a degradation of the Ge energy resolution mainly at 90° relative to the beam direction. In order to reduce this effect, different types of detectors have been imagined and studied (stacks of planars, segmented coaxial detector) for the phase 2 with the aim to increase also the total efficiency. Finally, a new Ge detector has been designed [9] at Strasbourg : the clover detector. It consists of four coaxial N-type Ge detectors arranged like a four-leaf clover (Figure 3) and shaped to enable a close packing of the counters.

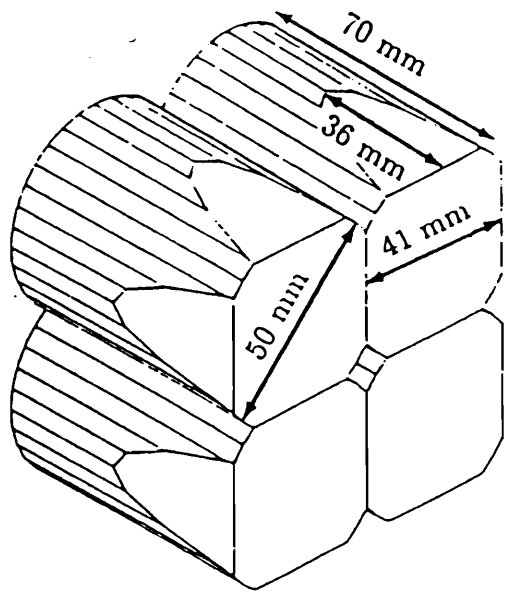

Figure 3 : *Schematic view of a Ge clover detector with the crystal sizes.*

Besides the reduction of Doppler broadening this detector offers other advantages as, for example, a high sensitivity to linear polarization of the γ-rays which means that it may be used as a γ-ray polarimeter. The development of this new composite detector and its use for the phase 2 have given in a large improvement of the EUROGAM performances. An example is given in Figure 4 for the energy resolution. The two spectra represent a part of the yrast superdeformed band in ^{149}Gd. The resolution of the γ-ray at 1.44 MeV, ΔE_γ (full width of half maximum, FWHM) goes from 6.1 keV for EUROGAM I to 4.8 keV for EUROGAM II which means a improvement of more than 25 % by using the clover detectors.

For the second phase the structure around 90° has been replaced by two rings of 12 clover detectors. The previous geometry has been preserved for the forward and backward parts (15 detectors each). This means that EUROGAM phase 2 consists of 54 modules (Ge + BGO) : 30 tapered Ge and 24 clover Ge detectors surrounded by BGO escape suppression shields (Figure 5).

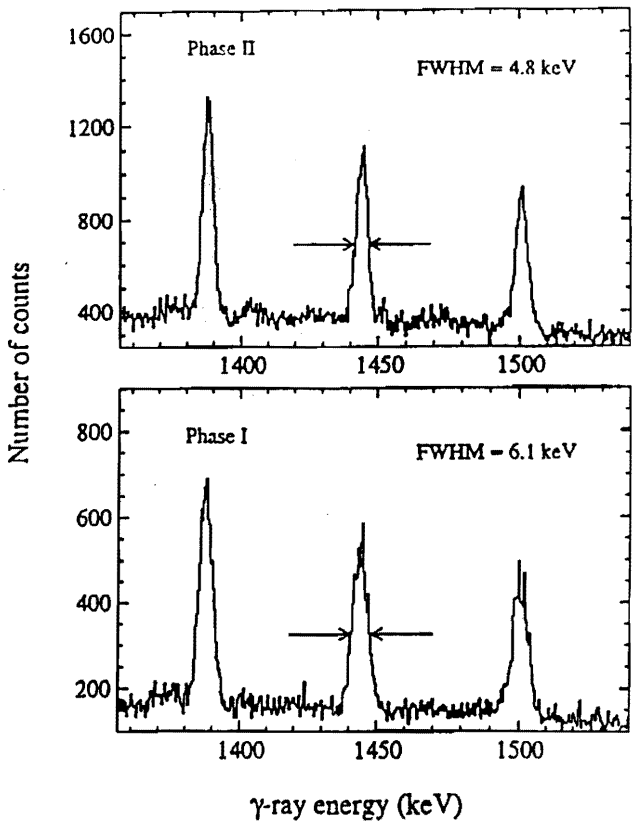

Figure 4 : *Comparison of the energy resolution (FWHM) for a peak at 1.44 MeV between EUROGAM phase 1 and phase 2 [10].*

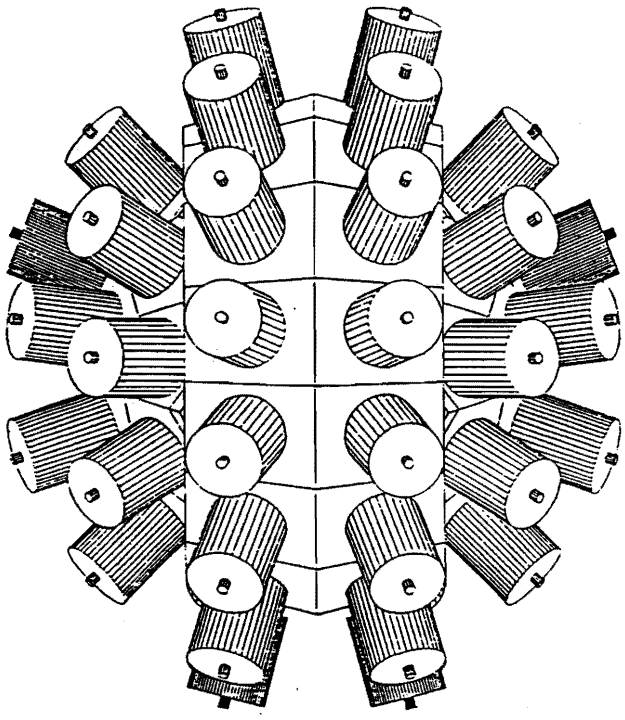

Figure 5 : *EUROGAM general structure for phase 2; the detectors between 60° and 120° are replaced by clover detectors.*

Besides the large increase of resolving power : R $\sim$ 8-11 according to the experiment, the gain in the total photopeak efficiency ($\varepsilon_T \sim 8\,\%$) gives us the possibility to measure higher coincidence orders and the detection limit reaches 5×10^{-5}.

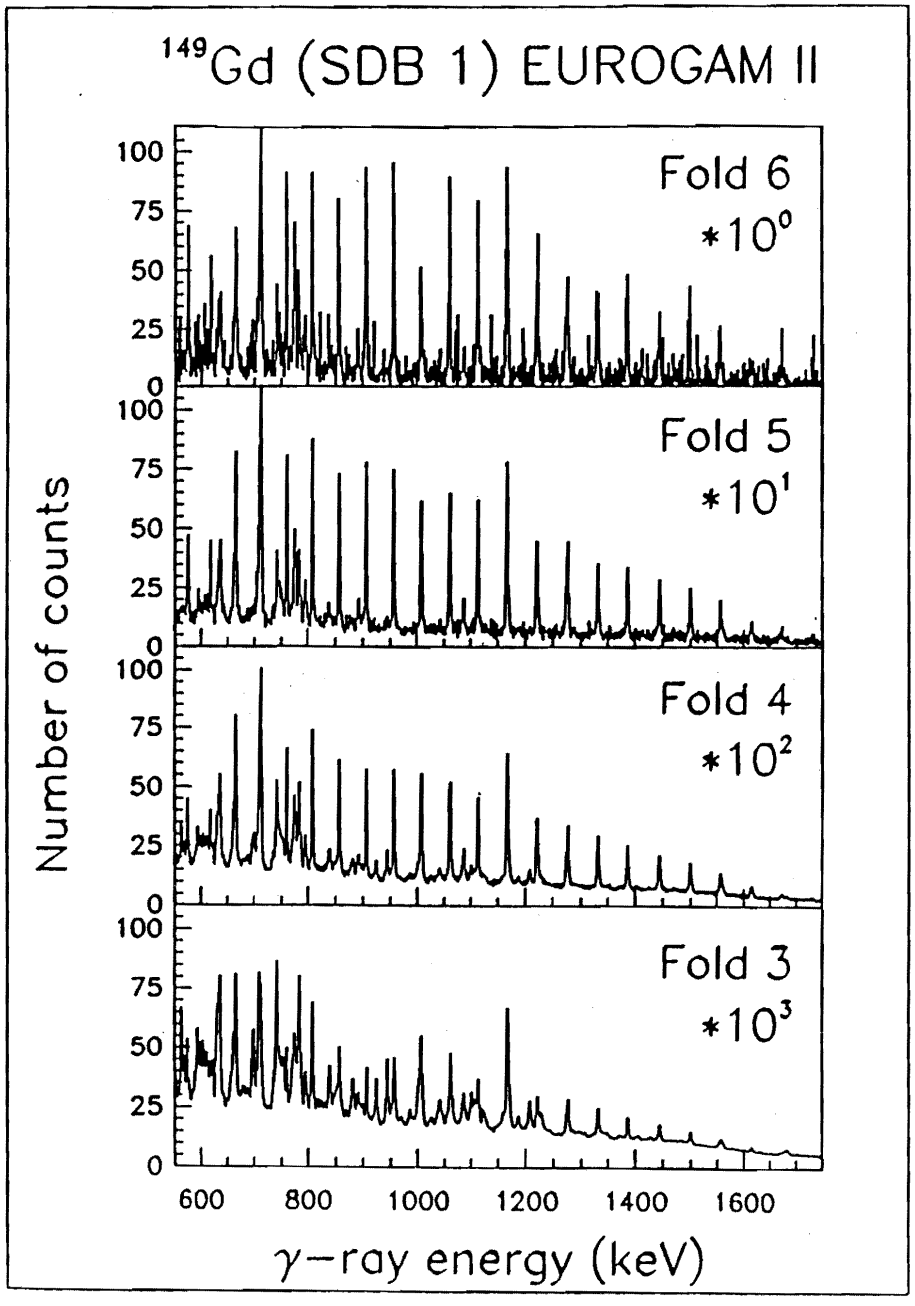

Figure 6 : *Partial γ - ray spectra associated with the yrast superdeformed band in ^{149}Gd. The spectra have been obtained by summing selected combinations of (f minus one) - dimensional energy windows set on f - fold coincidence events (f = 3 to 6). No background has been substracted. Spectra are labeled by the fold f and the vertical scales should be multiplied by the factors indicated [11].*

It is really important to have high fold events to select the rare phenomena we want to study in a nucleus. This can be illustrated with Figure 6. The spectra represent the yrast superdeformed band in ^{149}Gd populated by the reaction ^{124}Sn (^{30}Si , 5n) ^{149}Gd at 160 MeV. The beam was from the recently commissioned Vivitron tandem Van de Graff accelerator at the Centre de Recherches Nucléaires in Strasbourg. Gamma - rays have been detected in the EUROGAM 2 spectrometer. A condition has been imposed for the unsuppressed fold which had to be greater or equal 9. All these spectra have been obtained without background subtraction. 17 transitions have been used to select the band. Events with different suppressed folds have been selected for the spectra : fold 3 for the spectrum 1 (bottom) with all the combinations of 2 gates in the 17 transitions; fold 4 for the spectrum 2 (combinations of 3 gates); fold 5 for the spectrum 3 (combinations of 4 gates) and finally fold 6 for the spectrum 4 (top) with all the combinations of 5 gates in the 17 transitions of the yrast superdeformed band in ^{149}Gd [11]. The improvement in these spectra is spectacular especially the peak to background ratio and it is really important in particular for a precise measurement of the γ - ray energies or their intensities.

For EUROGAM, the large number of counters coupled with the need for excellent energy resolution, precise timing information and a very high data rate required a new concept in electronics and data acquisition. Another important feature was the need to be able to control and monitor the complete system with computers. The VXI standard has been chosen for these reasons and for the possibility of development of large electronic cards [6, 12].

3. Results

EUROGAM phase 1 has been operational at the Nuclear Structure Facility at Daresbury (U.K.) from October 1992 to March 1993. EUROGAM phase 2 is operational since September 1994 near the new Vivitron tandem Van de Graff accelerator at the C.R.N. Strasbourg (France). A large part of the experiments performed with EUROGAM concerned the study of the superdeformation in different mass regions ($A \sim 80$, $A \sim 130$, $A \sim 150$ and $A \sim 190$) and the new phenomenon of collective dipole bands observed in the mass $A \sim 190$ region. The following examples represent some of the most outstanding results obtained with this array.

3.1 Staggering effect in the superdeformed bands.

The so - called staggering effect consists of a very small displacement of the superdeformed energy levels compared to a smooth reference and it has been first discovered in the nucleus ^{149}Gd [11, 13]. The yrast superdeformed band in ^{149}Gd has been studied with EUROGAM phase 1 using the reaction ^{124}Sn (^{30}Si , 5n) ^{149}Gd at a bombarding energy of 158 MeV. The moment of inertia of the yrast superdeformed band in ^{149}Gd, plotted in Figure 7 as a function of the angular momentum, exhibits an unexpected bifurcation at high rotational frequency ($\hbar\omega \geq 0.79$ MeV) [11, 13].

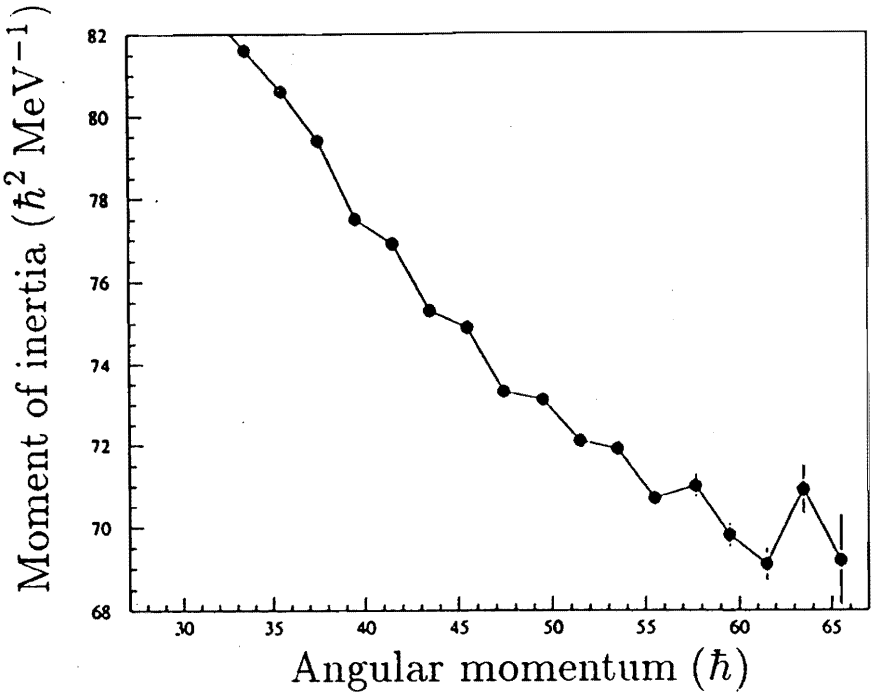

Figure 7 : *Dynamical moment of inertia of the yrast superdeformed band in* ^{149}*Gd as a function of the angular momentum [11, 13].*

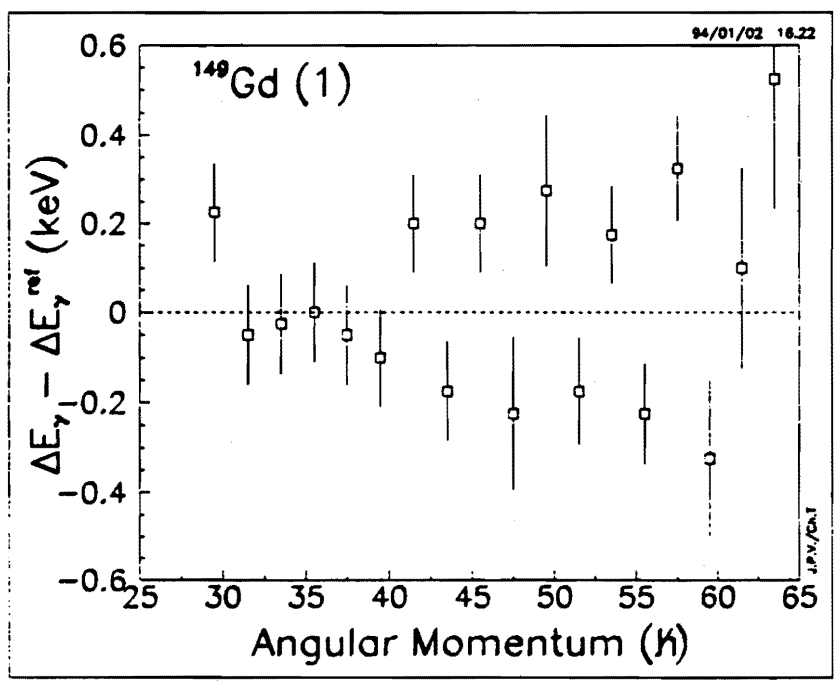

Figure 8 : *Energy differences* ΔE_γ *between two consecutive* γ *- ray transitions of the superdeformed band in* ^{149}*Gd as a function of the angular momentum after substraction of a smooth reference given by* $\Delta E_\gamma^{\rm ref}(I) = \frac{1}{4}[\Delta E_\gamma(I+2) + 2\Delta E_\gamma(I) + \Delta E_\gamma(I-2)]$ *[11, 13].*

The amplitude of the oscillations is weak but definitely outside the experimental error bars so that the staggering effect certainly originates from a perturbation of the superdeformed energy levels. The effect of the perturbation on the energy differences ΔE_γ between two consecutive γ-ray transitions of the superdeformed band in ^{149}Gd have been experimentally determined by comparing the ΔE_γ (I) values with a smooth reference calculated with the expression : $\Delta E_\gamma^{\rm ref}(I) = \frac{1}{4}[\Delta E_\gamma(I+2) + 2\Delta E_\gamma(I) + \Delta E_\gamma(I-2)]$. ΔE_γ - $\Delta E_\gamma^{\rm ref}$ is plotted in Figure 8 as a function of the angular momentum. The staggering effect sets in just above $35\hbar$. The $\Delta I = 2$ rotational band is perturbed and two $\Delta I = 4$ rotational sequences emerge with an energy splitting of about 120 eV which means that the levels are alternately pushed up and down by 58 ± 11 eV [11, 13]. Considering the fact that these superdeformed states are located at an excitation energy of $\sim$20 MeV above the ground state, the observed shifts correspond to a 10^{-6} perturbation on the level energies.

Although very small, this experimental observation indicates the possible presence of a new symmetry in the nuclear Hamiltonian. Theoretically, the idea of a Y_{44} perturbation in the nuclear shape, with the associated $C_{4\nu}$ point symmetry for the rotational Hamiltonian, has been suggested [14, 15]. However, the mechanism leading to this perturbation is rather different from these two approaches since the angular momentum can be considered aligned along a direction near the long axis of the prolate superdeformed nucleus [14] or perpendicular to this axis [15].

The C_4 oscillations have been observed for the first time in the yrast superdeformed band in ^{149}Gd but the yrast superdeformed bands in ^{151}Tb and ^{152}Dy, studied with the same experimental device, do not show the effect. On the other hand, the same oscillations have been recently observed, using EUROGAM phase 2, in the first excited superdeformed band in ^{147}Gd [11]. The same phenomenon has been observed in the mass A$\sim$190 region. There are some indications that the staggering effect is also present in three superdeformed bands in ^{194}Hg [16]. In this experiment, using the early implementation of GAMMASPHERE [6], excited states in ^{194}Hg have been populated with the reaction ^{150}Nd(^{48}Ca, 4n)^{194}Hg at beam energy of 206 MeV. The staggering in the energy levels is smaller than for the Gd nuclei and some doubts remain because of the large error bars [16].

3.2 Decay-out of superdeformed bands in ^{192}Hg and ^{194}Pb.

A common feature concerning the superdeformed bands is that, after a impressive series of up to 20 transitions, the transition intensity suddenly disappears within one or two transitions around spin $10\hbar$ and $25\hbar$ in the mass 190 and 150 regions, respectively. This sudden decay from the superdeformed states to normal-deformed states raises many interesting questions. To find the linking transitions between superdeformed and normal-deformed states would allow to measure the spin and excitation energy of the superdeformed states to be compared with the theoretical predictions, but also to better understand the superdeformation phenomenon itself.

Two experiments have been carried out with EUROGAM phase 1 to investigate the decay-out of the superdeformed bands in ^{192}Hg and ^{194}Pb [17,18]. Superdeformed states in the two nuclei have been populated in the ^{160}Gd(^{36}S,4n)^{192}Hg and ^{184}W(^{16}O,6n)^{194}Pb reactions at beam energies of 159 MeV and 116 MeV respectively. Superdeformed bands may depopulate through two distinct mechanisms : discrete transitions or statistical decay. The spectra of γ-rays following the decay of the superdeformed bands in ^{192}Hg and ^{194}Pb comprise both quasicontinuous components and sharp lines as shown in Figure 9 which represent, for ^{192}Hg (top) and ^{194}Pb (bottom), a comparison between a spectrum triple gated on the superdeformed band and the total spectrum [17,18].

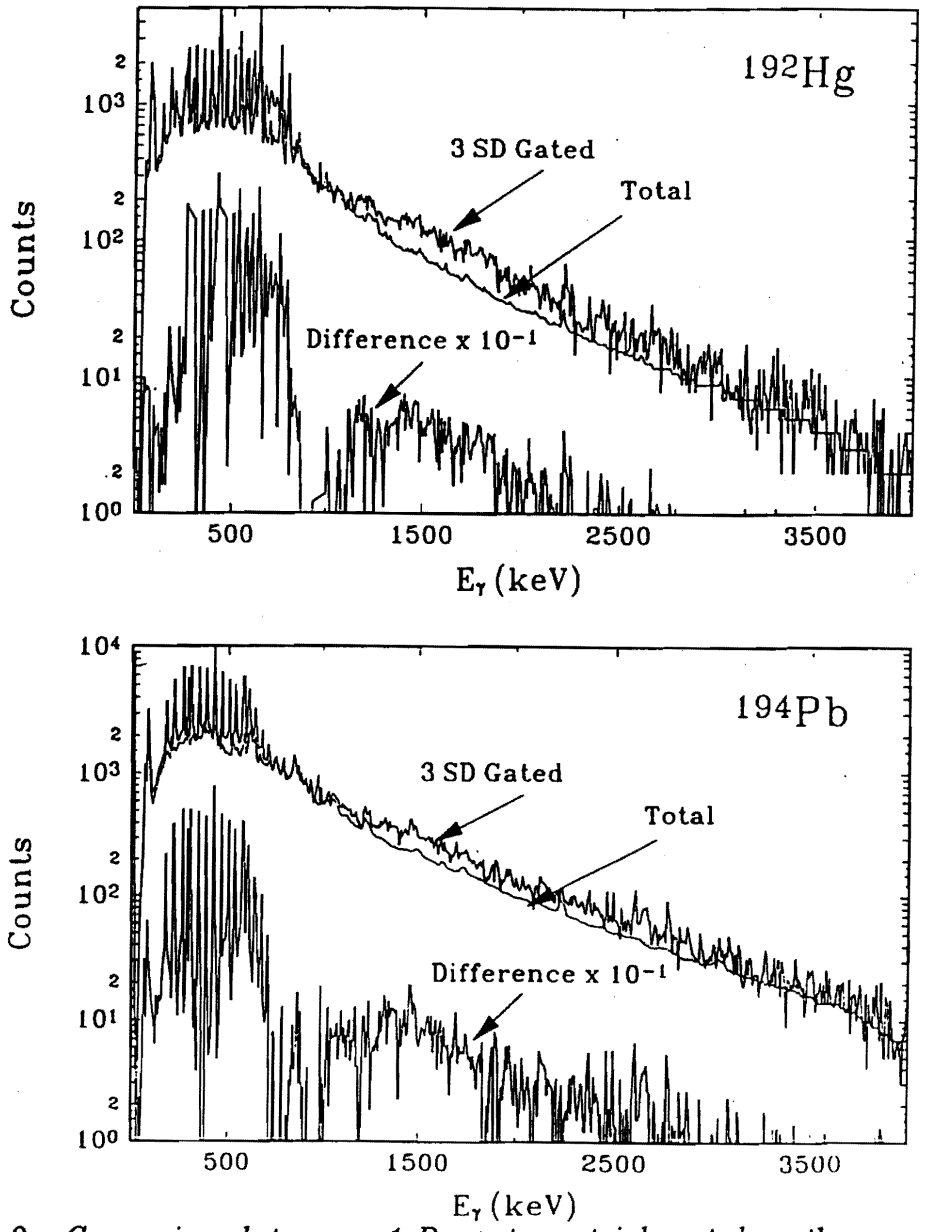

Figure 9 : *Comparison between a 1-D spectrum triple gated on the superdeformed band and the total spectrum obtained during the experiment for ^{192}Hg (top) and ^{194}Pb (bottom) [17, 18].*

For ^{192}Hg, the difference spectrum shows clearly, in the 1 to 2 MeV region, a bump which has been interpreted as due to statistical transitions involved in the decay-out process. An average excitation energy above yrast of 4.3 ± 0.9 MeV has been estimated for the decaying superdeformed states with a multiplicity of 3.2 ± 0.6 for the decay γ-rays [17]. For ^{194}Pb, the quasicontinuum bump is still present in the 0.8 to 2.5 MeV region and it can also be related to the decay-out process. A similar experiment has been realized using GAMMASPHERE Early Implementation to study the decay-out of the superdeformed band in ^{194}Pb [19]. Figure 10 shows the backgroung-substracted double-gated coincidence spectrum obtained during this experiment and its seems to illustrate the apparent lack of statistical transition strength in ^{194}Pb. These two conflicting results bring to the fore the problem of the background substraction in these analysis.

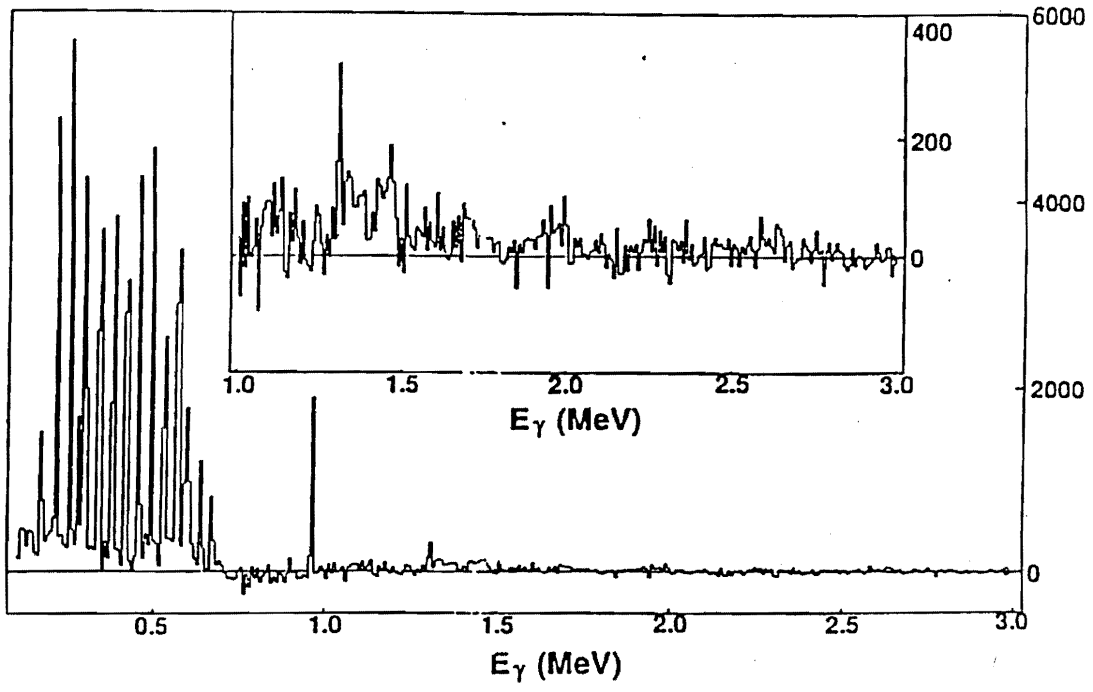

Figure 10 : *Backgroung-substracted double-gated coincidence spectrum for the ^{194}Pb superdeformed band [19].*

Concerning the discrete transitions mechanism, besides the known lines, additional new lines have been observed in coincidence with both the superdeformed band and the low-lying transitions at normal deformations in both nuclei and their energies range from a few hundred keV to 3 MeV [18]. Their intensities are in average less than 6% of the superdeformed bands intensities and they are certainly some of the connecting transitions between the superdeformed and normal-deformed states in the two nuclei but it is still impossible to establish the missing level schemes.

3.3 Collective oblate dipole bands in the A~190 mass region.

Recently, intense dipole bands, corresponding to an oblate axial deformed shape of the nucleus, have been observed at high spin in some nuclei of the mass A = 190 region.

An experiment using the TESSA 3 array has been carried out to study the nucleus ^{198}Pb and it has revealed for the first time the existence of a regular $\Delta I = 1$ collective structure which has been interpreted in terms of an oblate high-K two-proton - two-neutron configuration [20]. Since this first discovery, many other dipole bands have been observed in Bismuth, Lead and Mercury isotopes but, as for the superdeformed bands, these bands were not connected to the known low-lying states and therefore their spin and excitation energy values were unknown, which prevented the precise identification of the neutron and proton configurations involved in these states.

New important results have been obtained using EUROGAM, in particular new dipole bands have been observed in ^{194}Pb [21] and ^{192}Hg [22] and, for the first time, they have been connected to the low-lying levels.

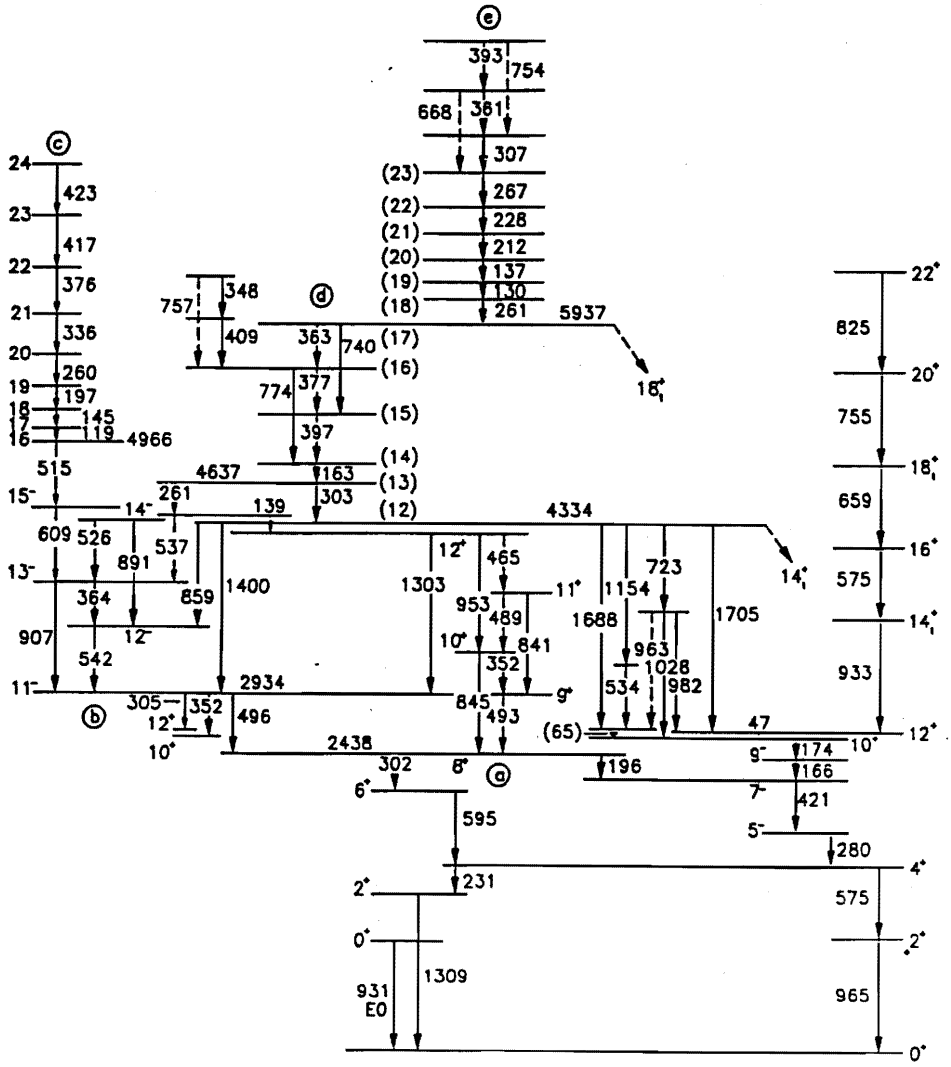

Figure 11 : *Partiel level scheme related to the dipole bands in ^{194}Pb [21].*

The first experiment has been performed using the early implementation of EUROGAM phase 1 (30 Compton-suppressed Ge detectors) and excited states in ^{194}Pb have been populated with the reaction ^{162}Dy(^{36}S, 4n)^{194}Pb at a bombarding energy

of 162 MeV [21]. During the analysis of this experiment, angular distribution information has been extracted from coincidence data. The level scheme (Figure 11) has been extended up to an excitation energy of 8.2 MeV and spin 26 $\hbar$ and two regular dipole γ-ray cascades ((c) and (d),(e)) have been observed and connected to the previously known low-lying states for the first time. The decay-out of the second structure ((d),(e)) is very fragmented : ten transitions have been identified with an energy range from 700 to 1705 keV and an intensity of a few percents of the reaction channel. From the excitation energies, spin values, behaviours of the moments of inertia and alignments, the following multiparticle configurations have been proposed for these high-spin structures in ^{194}Pb [21] :

$\{\pi 9/2^- [505] \pi 13/2^+ [606]\} \{\nu i 13/2\}^2$,
$\{\pi 9/2^- [505] \pi 13/2^+ [606]\} \{\nu f 5/2 \nu i 13/2\}$,
$\{\pi 9/2^- [505] \pi 13/2^+ [606]\} \{\nu f 5/2 (\nu i 13/2)^3\}$.

In this interpretation, the very regular dipole bands correspond to the presence of at least two i13/2 neutrons.

In the second experiment using the EUROGAM phase 1 full array, the ^{192}Hg nucleus has been populated via the ^{160}Gd(^{36}S, 4n) reaction at 159 MeV [22]. Angular distribution information has also been extracted from coincidence data. The level scheme of ^{192}Hg (Figure 12) has been extended up to 10.4 MeV excitation energy and spin 34 $\hbar$. Two new structures, composed of competing $\Delta I = 1$ and $\Delta I = 2$ transitions, have been observed and, for the first time in Mercury isotopes, some links with the known low-lying levels have been established. The two bands are based on states located at 6.879 MeV ($I = 23^-$) and 6.304 MeV ($I = 22^+$) excitation energy. These bands are strongly populated in the reaction : within the EUROGAM trigger conditions used in this experiment, the 337 keV (band (a)) and the 334 keV (band (b)) transitions represent respectively 10 % and 12 % of the reaction channel intensity. The bands are seen up to excitation energies E = 10.467 MeV (band (a)) and E = 10.039 MeV (band (b)) and a spin $I = 34\hbar$. The first band is more regular than the second one and shows a regular behaviour for the transition probabilities B(M1)/B(E2) ratios with a mean value of $5.5 (\mu_N/eb)^2$ [22]. These experimental results have been discussed in terms of mean-field Hartree-Fock plus BCS calculations [23] using the effective interaction SkM*. For this nucleus, the absolute minimum of the deformation potential energy curve occurs for an oblate shape corresponding to a charge quadrupole moment of -4.8 eb. The corresponding valence multi-quasiparticle states (2qp, 4qp, 6qp, 8qp) have been calculated and a stabilization around the same oblate shape has been observed. In this theoretical scheme, the new bands are proposed to originate from deformation-aligned quasi-proton excitations, $\pi(i_{13/2} * h_{9/2})_{K^\pi=11^-}$ and $\pi(h_{9/2})^2_{K^\pi=8^+}$ coupled to rotation-aligned quasi-neutrons $\nu(i_{13/2})^n$ and quasi-proton $\pi(h_{11/2})^2$ excitations. The comparison between the dipole bands observed in Hg isotopes and those observed in Pb isotopes shows that the transition probabilities B(M1)/B(E2) ratios are smaller in Hg isotopes. This can be interpreted as different configurations leading to smaller B(M1) values (rotation-aligned quasi-protons $\pi(h_{11/2})^2$) or to higher deformation in Hg isotopes. The last possibility should be discussed in terms of GCM calculations [24].

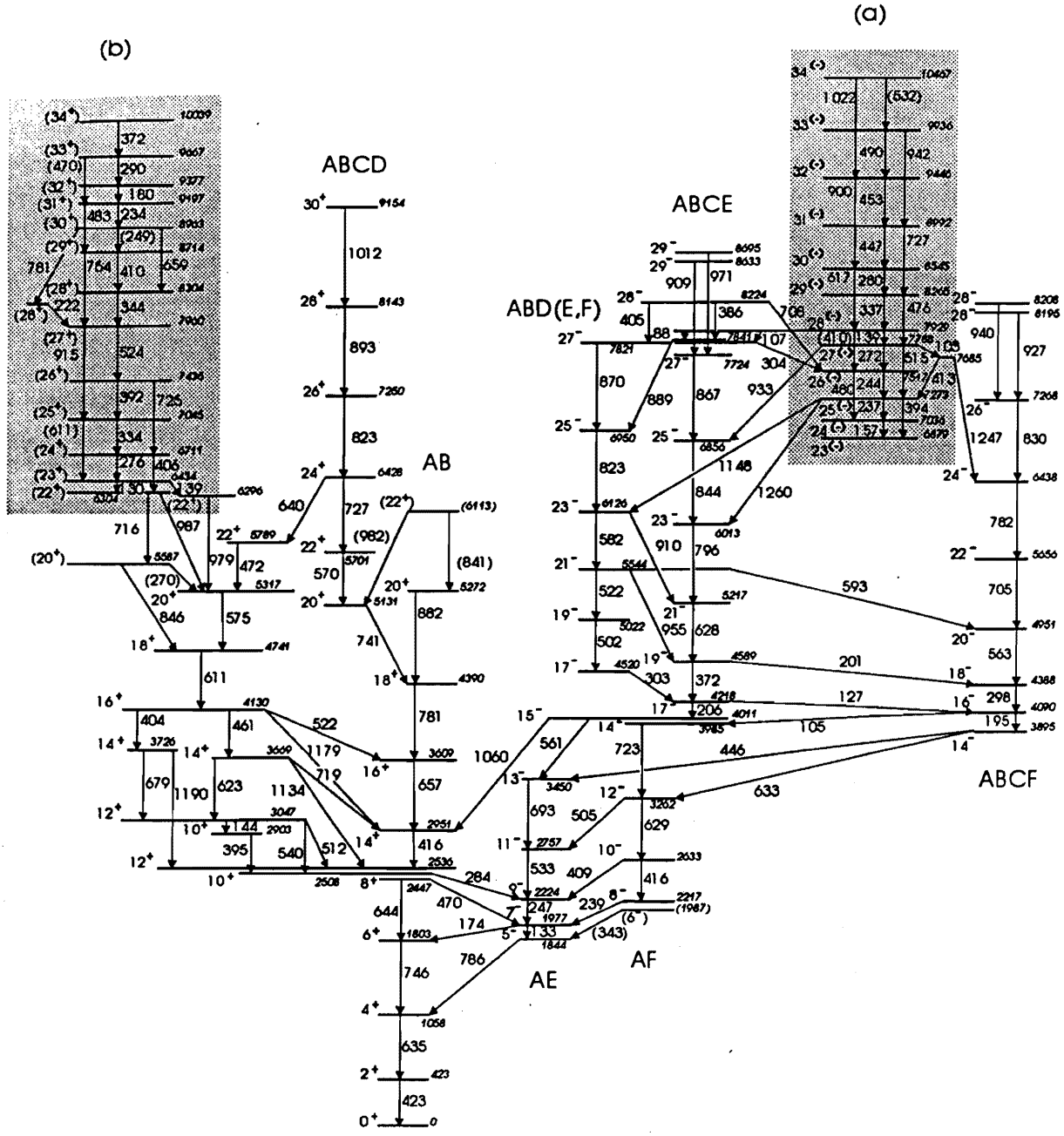

Figure 12 : *Partial level scheme of the* ^{192}Hg *nucleus populated in the* $^{160}Gd(^{36}S, 4n)$ *reaction showing the two new dipole bands* 23^- *and* 22^+ *and their decay via, respectively negative and positive parity bands [22].*

For all these dipole bands in the A~190 mass region, further experimental studies measuring in particular the half-lives of these states are necessary to confirm this collectivity.

These results are some of the most outstanding obtained with the EUROGAM spectrometer and many other experiments have been carried out successfully with the phase 1 and it continue now with the phase 2. All these new discoveries prove the performances of the EUROGAM array which has allowed us to push back the observational limits in a nucleus and to progress in the understanding of nuclear structure. But some questions remain open and we need to improve this spectrometer to try to solve these problems. This is the aim of EUROBALL III.

3. EUROBALL III

The EUROBALL III array is the result of cooperation between a group of european countries (France, United Kingdom, Germany, Italy, Denmark, Sweden) [6]. It will be based on the EUROGAM II array and will retain the 24 clover detectors in two rings near 90°. The backward part of the detector will consist of 15 cluster detectors [25], composed of seven hexaconical tapered Ge detectors, and will cover angles between 120° and 180°. The forward sector (angles between 0° and 60°) will be covered by EUROGAM I and GA.SP detectors. This arrangement (Figure 13) will used 231 individual Ge detectors for the first phase. The total photopeak efficiency is expected to be 10-11 %, the resolving power is estimated to be 9.2, resulting a detection limit of 10^{-5}.

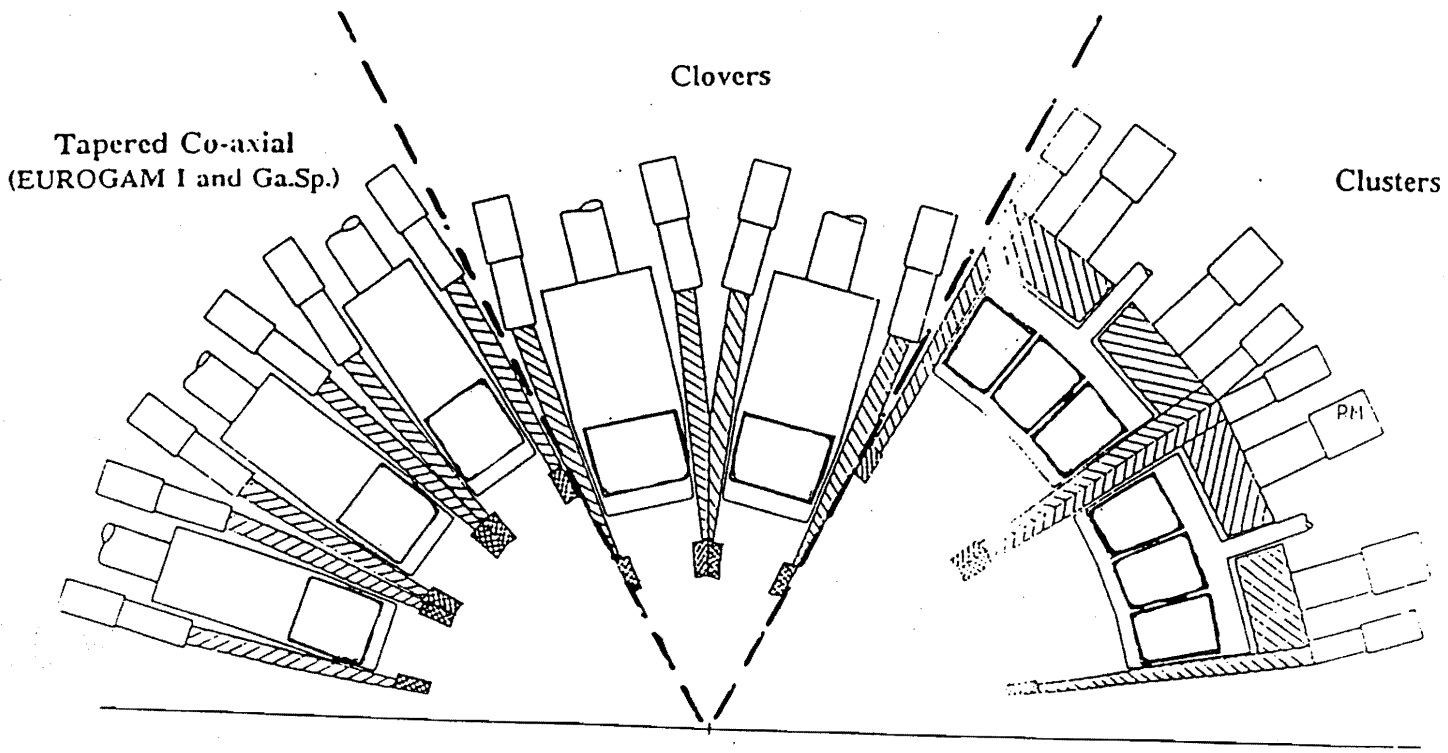

Figure 13 : *General structure for EUROBALL III.*

The EUROBALL III array is expected to be operational in 1997 at Legnaro (Italy) for 14 to 16 months. During this time, there will be developments and tests of new composite detectors. EUROBALL will move to Strasbourg (France) in the middle of 1998 and will be operational for a new period of 14 to 16 months with the new detectors.

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