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Nuclear Gamma Spectroscopy and the Gamma-Spheres

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Abstract

High resolution gamma-ray spectroscopy is one of the most powerful tools to study the structure of atomic nuclei. Significant advances in the development of increasingly sensitive instrumentation have taken place in recent decades. The latest 4π gamma-ray arrays, or “Gamma-Spheres”, continue to reveal fascinating new scientific phenomena at the limits of isospin, excitation energy, angular momentum, temperature, and charge. Another huge leap forward in the resolving power of Ge based detection systems is now taking place via the development of gamma-ray tracking arrays which when combined with new accelerator developments, assures a most exciting future to this field. These technical advances also have a wide range of application spin-offs.

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1. Introduction

Gamma-ray spectroscopic techniques play a vital role in our investigations into the properties and behavior of the unique strongly interacting aggregation of fermions that we call the atomic nucleus. These studies of the gamma-ray emissions from excited nuclei reveal an extremely rich system that displays a wealth of static and dynamical facets. The number of nucleons is sufficient (< 300) to allow correlations but it is still finite. Thus nuclei exhibit a variety of collective properties yet are simple enough to display both single-particle properties and a single-particle basis of these collective effects. The remarkable diversity of phenomena and symmetries exhibited by nuclei continues to surprise and fascinate scientists as unexpected properties are continually revealed by new experimental investigations arising from the development of increasingly sensitive instrumentation and new accelerator developments.

Every major advance in gamma-ray detector technology has resulted in the discovery of new phenomena bringing significant fresh insight into the structure of nuclei. The different time periods or era’s associated with different detector technical advances are presented in Fig. 1. At the present time we find ourselves at the transition from the “Gamma-Sphere’s” or large 4π arrays of escape-suppressed spectrometers, such as Gammasphere and Euroball, to the beginning of the development of 4π Ge shell arrays, such as GRETA (Gamma Ray Energy Tracking Array) in the USA and AGATA (Advanced Gamma Tracking Array) in Europe, see Ref. [1] and references therein. These latter systems will abandon physical suppression shields and instead employ the technique of gamma-ray tracking in electrically segmented Ge crystals. As a first step towards the implementation of these 4π Ge arrays the ~1π systems GRETINA (Gamma Ray Energy Tracking In beam Nuclear Array) in the US and the first phase of AGATA (Advanced Gamma Tracking Array) in Europe have been recently constructed and have just begun their initial physics campaigns.

This article will summarize significant recent developments in high-resolution gamma-ray spectroscopy. A special emphasis is placed on the new revolutionary technology of gamma-ray tracking. Descriptions of a number of current large gamma-ray arrays in operation around the world will be given together with an outlook into the future of this exciting field. More detailed technical reviews of many of these recent developments in Ge based detectors along with a variety of physics highlights may be found in Refs. [2,3]. Developments and highlights from the previous two decades are covered in Refs. [4,5].

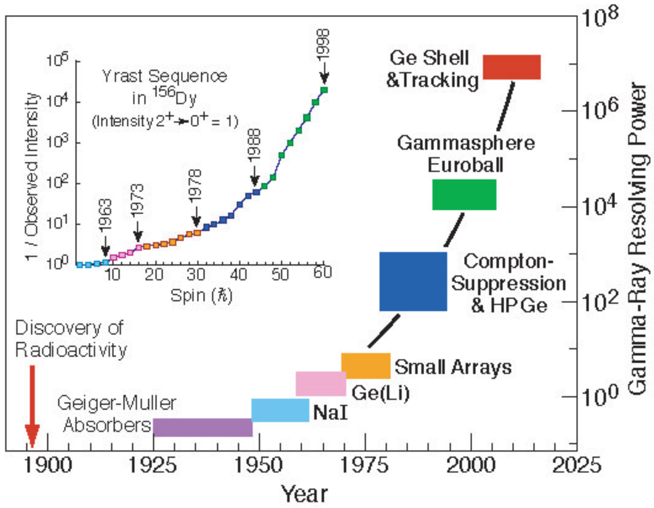

Fig. 1. The evolution of γ-ray detector technology. The calculated gamma-ray resolving power is a measure of the ability to observe faint emissions from rare and exotic nuclear states. This is illustrated in the upper left insert, which indicates the strong relationship between resolving power and the inverse of the experimental observational limit.

2. An Example: The Spectroscopy of ^{158}Er through the Decades

An excellent example of the evolution of gamma-ray detector systems through the decades, which illustrates the ability to discover new physical phenomena, comes from the study of the yrast (lowest energy state for a given angular momentum) states in the rare-earth nucleus, ^{158}Er, as displayed in Figs. 2 and 3 (see also Refs [6,7,8] and references therein). At very low spin values the yrast states form a rotational band corresponding to a spinning collective structure with a low moment of inertia value of ~30% of the rigid body value, which reveals that superfluid behavior or pairing correlations play a significant role. However, with increasing angular momentum, or spin, the Coriolis force induces the breaking or rotational alignment, of specific high-j pairs of particles in a process known as "backbending" at spin I~14 for a pair of $i_{13/2}$ neutrons and at I~28 for a pair of $h_{11/2}$ protons. These rotational alignments cause large changes in the moment of inertia behavior. Another sudden change in the moment of inertia along the yrast line occurs at spin I~38. These features were all observed using Ge(Li) detectors with (now) relatively low resolving powers. It was only with the development of escape-suppressed arrays that this latter anomaly in the moment of inertia could be delineated and explained. It is now understood as a dramatic shape transition from a collective-prolate rotation to non-collective or weakly collective oblate configurations along the yrast line at spins 40−50. This transition manifests itself as energetically favored, fully aligned band termination states at 46^+, 48^-, and 49^-, see Fig 2.

It has taken two decades and the development of large 4π escape-suppressed gamma-ray detector arrays to discover what happens above "band termination" in ^{158}Er. Using the Gammasphere spectrometer a return to collective rotation at the highest spins was observed when rotational structures of very low intensity (~ 10^{-4} of the respective channel intensity) very high moments of inertia, and large quadrupole moments were found [7,8], see Fig. 3. These structures extended discrete line spectroscopy in this nucleus up to I ~ 65.

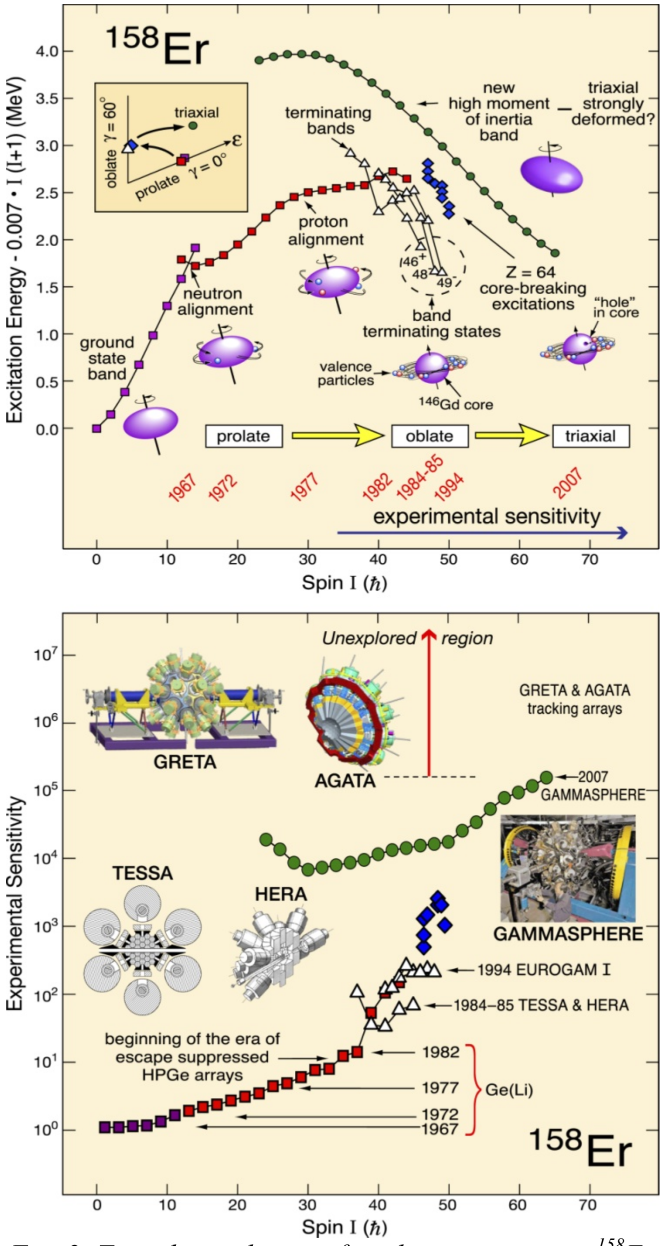

Fig. 2. Top: the evolution of nuclear structure in ^{158}Er with excitation energy and angular momentum (spin). The inset illustrates the changing shape of ^{158}Er with increasing spin within the standard (ε , γ) deformation plane. The parameters ε and γ represent the eccentricity from sphericity and triaxiality, respectively. Bottom: the experimental sensitivity of detection (proportional to the inverse of the observed gamma-ray intensity) is plotted as a function of spin showing the progression of gamma–ray detector techniques with time that are associated with nuclear structure phenomena in ^{158}Er. "TESSA", "HERA", "EUROGAMI", "GAMMASPHERE", "GRETA", and "AGATA" are specific names of gamma-ray detector arrays.

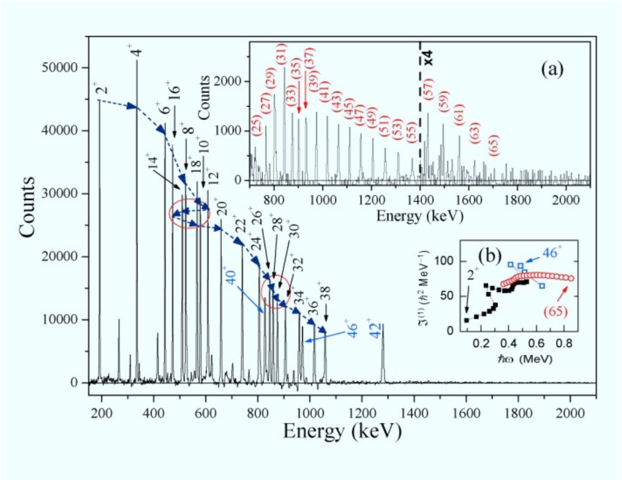

Fig. 3. Spectrum of gamma rays representative of the yrast band in ^{158}Er in coincidence with the 44^+ to 42^+ gamma-ray transition. Transitions are all labeled with the states (spin and parity) from which they decay. The observed neutron (Energy~550 keV, spin I~14) and proton (Energy~850 keV, I~28) rotational alignments are marked in red circles. Inset (a): spectrum representative of the strongest collective band at ultra-high spin observed in ^{158}Er (band 1). The portion of this spectrum above 1400 keV has been magnified by a factor of 4. The spins assigned are tentative and the parity of the sequence is not known. Inset (b): kinematic moments of inertia, $J^{(1)}$, as a function of rotational frequency hω, for the yrast sequence (collective prolate states: filled squares; non-collective oblate states: open squares) and band 1 (open circles) in ^{158}Er.

3. Modern High Resolution Gamma-ray Spectroscopy

The most important properties of a gamma-ray detector array are: (i) high efficiency in detecting incident gamma rays, (ii) high resolution resulting in very narrow full energy peaks, (iii) high ratio of full-energy to partial-energy events, (iv) high counting rates, and (v) high granularity to localize individual gamma rays and reduce the probability of two gamma-ray hits in one detector from the same event. For gamma rays in the MeV range, by far the best combination of these properties is given by semiconductors made of high-purity germanium (Ge) crystals. The largest such crystals that can currently be produced commercially are cylinders about 10 cm in diameter and 10 cm long which, for about 28% of incident 1 MeV gamma rays, produce a full-energy peak with a full width at half its maximum height of about 2 keV. To improve peak to background performance escape suppression techniques have been employed. To improve efficiency a number of Ge crystals have been placed together in the same cryostat in for example clover (four) and cluster (seven) detectors.

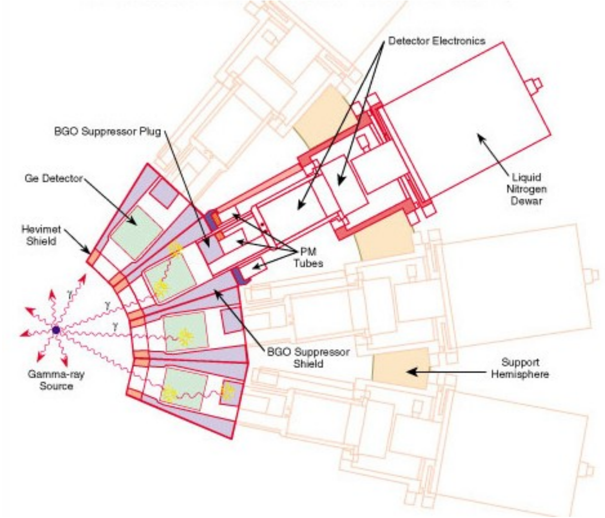

Fig. 4. Schematic of a modern escape-suppressed spectrometer array.

3.1 The Escape-Suppression Principle: For a better ratio of full-energy to total recorded events (called the peak-to-total, or P/T ratio), the Ge detectors are surrounded by a dense scintillator (bismuth germanate (BGO) being the most common), which detects gamma rays that Compton scatter or escape out of the Ge crystal. This detection triggers the electronics system to reject or suppress the partial-energy pulse in the Ge detector, see Figs. 4 and 5. This results in an improvement in the Peak to Total ratio for a 1.3 MeV gamma-ray from about 0.28 for the bare crystal to about 0.6. This is an enormously important signal to background gain, without which high-fold coincidence measurements would not be practical. For example, for a typical situation in the Gammasphere spectrometer when six gamma rays hit separate Ge detectors, the fraction of events with full-energy photo-peaks rises by a factor of about 100 with escape-suppression. For increase in both efficiency and granularity, escape-suppressed detectors are assembled into arrays. The first such array, called TESSA (The Escape Suppressed Spectrometer Array) was set up at the Niels Bohr Institute in 1980 and consisted of five Ge(Li) detectors surrounded by NaI(Tl) shields. Many arrays worldwide were based on this escape suppressed technology, one of the latest being Gammasphere with ~100 HPGe crystals surrounded by BGO shields.

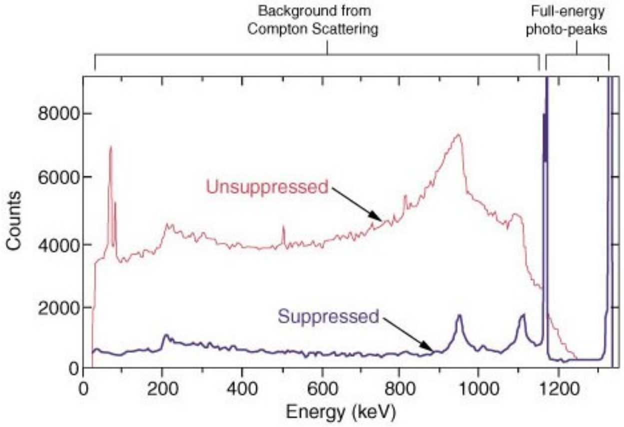

Fig. 5. Unsuppressed and suppressed spectra for ^{60}Co illustrating the huge gains in peak to background performance from the use of escape suppressed shielding techniques. Note the full energy photo-peaks have been normalized in the two spectra.

3.2 Gamma-ray Tracking

This is a time of great opportunity in nuclear spectroscopy. The development of radioactive beam capabilities around the world is opening a new landscape for discovery, and the connections between new nuclear structure studies and astrophysics, neutrino physics, and physics beyond the standard model are stronger than ever. New detector technologies have evolved that can meet the challenges of the new generation of experiments. The new technology of "γ-ray tracking", which was first discussed in the early-1990's is poised to revolutionize γ-ray spectroscopy in a way that large arrays of escape-suppressed γ detectors have done previously. Tracking arrays covering roughly 1π have been constructed in the US (GRETINA) and Europe (AGATA). Both devices are now engaged in physics campaigns. Hopefully the momentum in developing this technology to its full potential will continue towards full 4π GRETA and AGATA spectrometers, which will have unsurpassed sensitivity and discovery potential. These calorimeters will carry γ-ray spectroscopy into the next generation and will be needed to fully exploit the science opportunities at radioactive beam facilities as well as greatly increase the reach of stable beam facilities. In addition, gamma-ray tracking technology will have a wide range of important applications, such as in environmental monitoring, SPECT and PET medical imaging systems, and in homeland security situations.

This next major step in gamma-ray spectroscopy is therefore to abandon the concept of a physical escape-suppression shield, which greatly reduces the overall possible efficiency, and move towards the goal of a 4π Ge ball utilizing the technique of gamma–ray energy tracking in electrically segmented Ge crystals (see Fig. 6). With the new tracking technique, the position and energy of gamma-ray interaction points are identified in the detector segments. Since most gamma rays interact more than once within the crystal, the energy-angle relationship of the Compton scattering formula is used to track the path of a given gamma ray. The full gamma-ray energy is obtained by summing only the interactions belonging to that particular gamma ray. In this way, there are no vetoed Compton scatters in the suppression shields and scattered gamma rays between crystals are recovered. Thus, the planned 4π gamma-ray energy tracking arrays, GRETA and AGATA, will have a high overall efficiency, ~ 60% for a single 1 MeV gamma ray. Other key benefits of a tracking array include good peak-to-total ratio (~85%), high counting rate (~ 50 kHz) capability per crystal, excellent position resolution (~ 2 mm), the ability to handle high multiplicities without summing, the ability to pick out low-multiplicity events hidden in a high background environment, and high sensitivity for linear polarization measurements. For many experiments these 4π tracking arrays, as shown in Fig. 1, will provide orders of magnitude improvement in resolving power over present arrays.

Major technological advances and a huge amount of R&D have been necessary in order to make tracking spectrometers possible. These include the fabrication of highly segmented Ge detectors, the production of fast digital electronics, efficient signal analysis and tracking algorithms, and improved computational power. In the following, we will give a short summary of these technical accomplishments.

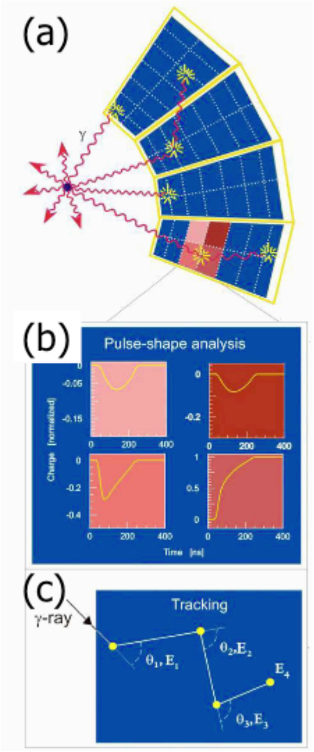

Fig. 6. Principles of the gamma-ray tracking technique. (a) A tracking array will consist of a closed shell of segmented Ge detectors. (b) Pulse-shape analysis of signals from segments containing the interaction(s), as well as analysis of transient signals in adjacent segments, allows the determination of the three-dimensional locations of the interactions, and their energies. (c) Tracking algorithms, which are based on the underlying physical processes such as Compton scattering or pair production, are able to identify and separate gamma rays and to determine the scattering sequence.

3.2.1 Segmented Ge Detectors

A critical detector technology is the manufacture of segmented coaxial germanium detectors, which provide signals with sensitivity for locating interaction points in three dimensions. Both GRETINA and AGATA use coaxial Ge crystals that are 36-fold segmented. These crystals have a length of ~9 cm and a diameter of ~8 cm at the rear. They are shaped into tapered irregular hexagon shapes for close packing into a spherical shell with high solid angle coverage. In AGATA the taper angle is 8^0 and for GRETINA/GRETA it is 10^0. These angles are a result of the efficient packing of the different numbers of detectors envisaged in the full 4π geometry. The geometries are based on tiling a sphere with the geodesic arrangement of irregular hexagons and regular pentagons; for AGATA the full array comprises 180 hexagons and 12 pentagons and GRETA 120 hexagons and 12 pentagons. These geometries result in 3 slightly different crystal shapes for AGATA and 2 for GRETA.

3.2.2 Digital Electronics

While the segmentation of the Ge crystal provides the initial position-of-interaction information in order to perform gamma-ray tracking, the positions and energies of the gamma-ray interactions in the Ge must be even more accurately determined from the signal waveforms. The position resolution is a key metric in the detector performance. It directly affects the efficiency, peak/total and the tracking efficiency of the array, as well as the effective energy resolution of the array when the emitting nucleus is travelling with high recoil velocity. AGATA and GRETA require state-of-the-art, purpose-built digital electronics and an associated data acquisition system to process the signals from the Ge crystals. Signals from the 37 preamplifiers of each detector (36 segments plus one central contact) are digitized. From the digitized pulse shapes processing units derive and provide additional parameters such as the channel number, the energy, the raw data samples from the leading edge of the pulse (trace), and a timestamp (in 10-ns steps). The "data-acquisition" section of the system collates and distributes the events to a computer cluster to perform signal decomposition, tracking and event reconstruction. These systems need to cope with a large numbers of channels, over 6000, and also with very high rates in each crystal, up to 50 kHz. The principle of the AGATA and GRETA systems is to sample these outputs with fast ADC's to preserve the full signal information so that accurate energies, times and positions can be extracted using the signal decomposition algorithms. Interfaces to enable "easy" electronic coupling of ancillary detectors to the acquisition system have been developed.

3.2.3 Signal Decomposition

In order to perform gamma-ray tracking, the positions and energies of the gamma-ray interactions in the Ge (usually several Compton scattering events, followed by photoelectric absorption) must be accurately determined from the signal waveforms. The procedure must handle cases where two or more interactions occur within one of the detector segments. For each crystal, a simulation is performed on a grid of points whose spacing reflects the sensitivity of the detector depending on the geometry, bias voltage, and crystal impurities. About 300,000 grid points per crystal are used with spacing varying from 0.5 to 3 mm. Measured signals are then compared with linear combinations of these simulated signals, as there are typically multiple interaction points in a given crystal, with the best fit giving the location and charge (energy) of the interaction points.

The signal-decomposition itself can be performed using a variety of algorithms, but to perform it in real-time, count-rate requirements and computer costs impose stringent limits on how much CPU time can be spent per event. At present, the GRETINA decomposition code uses a two-step process that starts with an adaptive grid search for one and two interactions per segment followed by a sequential quadratic programming (non-linear least-squares) fit which allows multiple interactions in multiple segments within a crystal. On the current generation of 2 GHz processors, the GRETINA algorithm requires less than 16 ms per CPU core per crystal.

It has been shown experimentally that the pulse shape algorithms developed for GRETINA and AGATA can achieve an average position resolution of better than 2 mm (RMS), which is sufficient for efficient gamma-ray tracking.

3.2.4 Tracking

The tracking process uses the energies and positions of the interaction points, produced by the signal decomposition, to determine the scattering sequence for a particular gamma ray. Algorithms have been developed to track events based on Compton scattering, pair-production and photo electric interactions. For events with multiple gamma rays, these algorithms are able to resolve and identify interaction points belonging to a particular individual gamma-ray. Gamma rays that deposit only partial energy in the detector are identified and rejected. Tracking efficiencies ranging from ~100% to 50% for gamma-ray multiplicities from 1 to 25, respectively have been calculated.

3.3. Auxiliary detectors

Auxiliary detectors used in conjunction with large gamma-ray arrays have played, and continue to play, a vitally important role since they augment tremendously the physics that can be achieved. These systems, which detect emitted light charged particles, or heavy recoils, or emitted neutrons, or plunger devices for precise timing measurements are all designed to physically combine with the large gamma-ray arrays. The latter are therefore different to other systems such as recoil separators, which also play a critical role in expanding the physics discovery potential of the large gamma-ray arrays. With gamma-ray tracking arrays auxiliary detectors and separators will perhaps play an even more important role. This is because in order to take advantage of the considerably smaller opening angle (~2^o in θ and ϕ for GRETINA/AGATA compared with 7^o for Gammasphere) and to make good use of this angular resolution for Doppler corrections the angle of the recoiling nucleus must now also be determined with comparable angular resolution.

Thus a new generation of auxiliary detectors, often based on previously successful systems used with Gammasphere and Euroball, are being constructed with higher segmentation and higher counting rate capabilities. The number of auxiliary detector systems is large and thus the reader is referred to the respective references and webpages of the gamma-ray systems discussed in the following section.

4. Large High Resolution Gamma-Ray Detector Arrays

As illustrated in Fig. 1, we are now in a transitional period moving from the era of large 4π escape-suppressed Ge arrays, illustrated by Gammasphere and Euroball, into the new era of Ge tracking arrays GRETINA/GRETA and AGATA. These major systems developed respectively by the collective gamma-ray communities in the US and Europe are summarized below along with a number of other significant large high-resolution gamma-ray arrays in current use around the globe. For further detailed information on these systems see Ref. [EbSi08] and references therein along with the webpages listed below.

4.1 GRETINA/GRETA

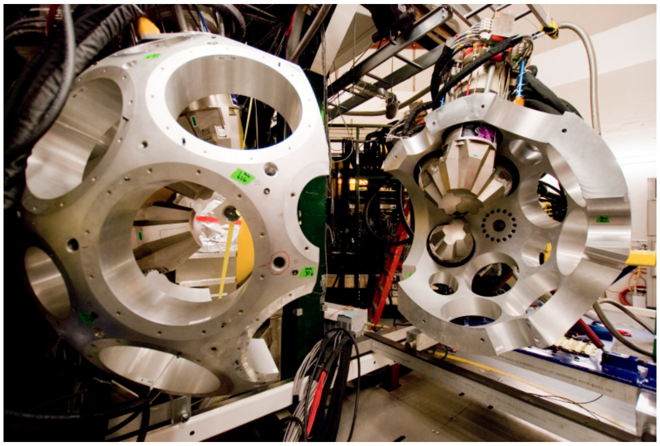

Fig.7. GRETINA at the NSCL.

GRETINA consists of seven modules, each containing four 36-fold segmented germanium detectors. It allows for localization of individual interaction points to an accuracy of 1-2 mm. These interactions are then tracked to reconstruct the energies of individual gamma rays and reject events with incomplete energy collection. The excellent position resolution allows more accurate Doppler-shift corrections, making GRETINA an ideal detector for measurements of gamma rays emitted in flight.

GRETINA was completed in April 2011. Following a year of testing and commissioning at LBNL by a collaboration of scientists from 12 U.S. Laboratories and Universities, GRETINA was successfully installed at the National Superconducting Cyclotron Laboratory, and began its first science campaign in summer 2012. Following the fast-beam campaign at NSCL, GRETINA is scheduled to move to Argonne National Laboratory in the middle of 2013 for its next science campaign at the ATLAS facility.

GRETINA is the first phase of GRETA and it is hoped to complete GRETA for “day one” experiments at the future Facility for Rare Isotope Beams (FRIB) at Michigan State University, which is due for completion at the end of the decade. Prior to FRIB operations, GRETA will enable forefront experiments at existing stable and radioactive beam facilities with its scientific reach increasing significantly as more detectors are added to GRETINA. The completion of GRETA requires 23 additional detector modules together with the associated electronics, computing, and mechanical support.

For further information about the GRETINA/GRETA project see:
http://www.physics.fsu.edu/GRETINA.org/

4.2 AGATA

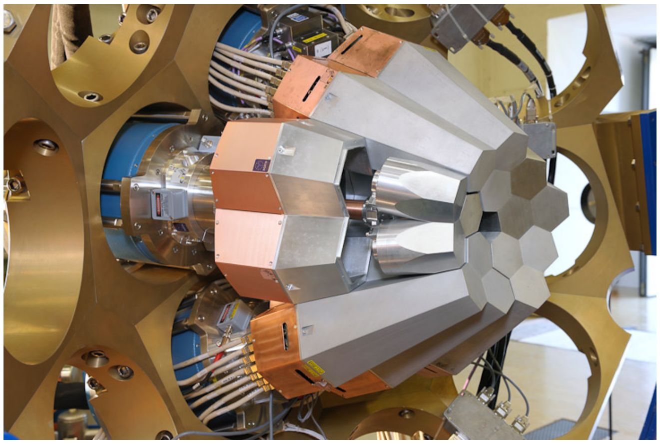

Fig. 8. The AGATA demonstrator at Legnaro National Laboratory.

The AGATA collaboration includes more than 40 institutes in 13 countries in Europe with the aim of developing and constructing a 4π tracking spectrometer. The first phase of the project consists of 15 detector capsules, with all the electronics and data acquisition, pulse shape and tracking algorithms and associated spectrometer infrastructure fully operational. In AGATA the Ge crystals are packed together in groups of three in a common cryostat.

The AGATA collaboration have agreed upon a MoU that defines the planning, funding, construction and operation of the device as it is built up from a 15 detector system towards the full 4π device. As with GRETINA, AGATA will be sited at different laboratories, taking full advantage of the different beams and facilities available, in order to maximize the range of science that can be addressed.

A series of commissioning experiments, with sources and stable beams, have been performed using the AGATA at Legnaro National Laboratory in Italy. An initial physics campaign began at Legnaro in early 2010 and the array is now at GSI in Germany for its second physics campaign where it is being used at the end of the Fragment Recoil Separator (FRS). In late 2013 it will be moved to the GANIL laboratory in France to use the wide range of radioactive ions from the coupled cyclotrons and SPIRALI/II. During these first three physics campaigns the number of modules will increase towards 60 systems, which is a 1/3 of the full AGATA system.

For further information about the AGATA project see:
http://www-win.gsi.de/agata/

4.3 Gammasphere

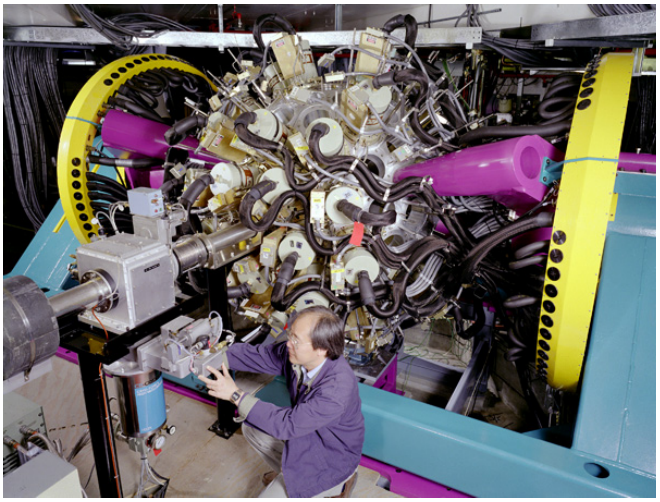

Fig. 9. Gammasphere was initially at Lawrence Berkeley National Laboratory and is now at Argonne National Laboratory.

Gammasphere was built by a consortium of US scientists from national laboratories and many universities. The project was coordinated by scientists at Lawrence Berkeley National Laboratory, where the device was first assembled. Gammasphere consists of a spherical shell of up to 110 large volume, high-purity germanium detectors, each about the size of a coffee cup, and enclosed in a BGO escape-suppression shield, see Fig. 4. It was commissioned in December 1995, although experiments using parts of the system, the so-called Early Implementation phase, began in mid 1993. Gammasphere moved to Argonne National Laboratory in 1997 for a two year period before returning to LBNL in 2001. Then in 2003 it returned to Argonne again where it has remained. The array has a total photopeak efficiency of ~9% at 1.3 MeV. As with other large Ge arrays a suite of powerful auxiliary detectors has been specially developed to enhance the resolving abilities of Gammasphere.

Even now, after nearly two decades of discovery, Gammasphere is still an extraordinarily powerful array and for many experiments, such as high multiplicity fusion evaporation reactions, it is the best in the world. In addition, it has just undergone a major upgrade, which significantly improves its performance, by allowing an increase rate in the Ge detectors and a higher overall data throughput rate of ~3-4. This has been achieved by replacing the ageing current analog electronics with a digital pulse processing data acquisition systems utilizing the GRETINA digitizers and trigger modules. Thus Gammasphere, aided by synergistic developments of the GRETINA project, will continue to perform cutting edge science for many years to come.

For further information see:
http://www.phy.anl.gov/gammasphere/index.html ,
http://nucalf.physics.fsu.edu/~riley/gamma/ , and
http://en.wikipedia.org/wiki/Gammasphere .

4.4 Euroball, JUROGAM I and II, CLARA, RISING, GASP and GALILEO

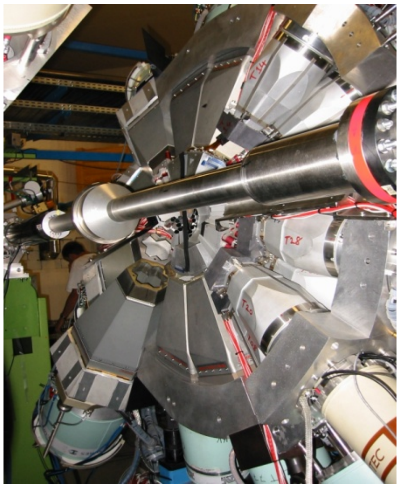

Fig. 10. The EUROBALL detector.

The European equivalent to Gammasphere was Euroball. This large project involved scientists from Denmark, France, Germany, Italy, Sweden and the UK. In the development of EUROBALL significent advances in detectors, electronics and data acquisition were made. In particular these included the revolutionary Clover and Cluster Ge designs, which were designed to increase the granularity of the array and thus minimize the double hit probability. In addition the effective Ge efficiency was increased by adding the energies of gamma rays which scattered between Ge crystals. Another useful benefit of the clover detector is its sensitivity to the linear polarization of gamma rays, which comes from the different intensities of events Compton scattered parallel or perpendicular to the reaction plane. The cluster detector combined seven Ge detectors into a single cryostat and surrounded by a BGO escape-suppression shield of a hexagonal shape. For optimum long term reliability another technical innovation was that the Ge detectors were hermetically sealed or encapsulated. Indeed, both GRETINA/GRETA and AGATA use encapsulated Ge detectors.

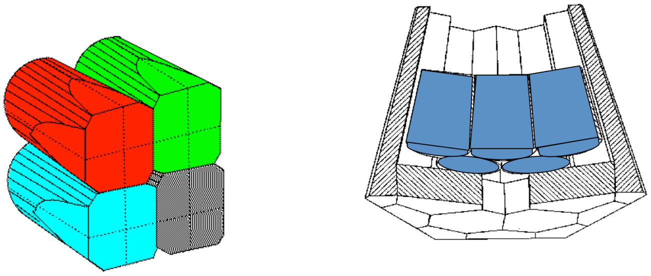

Fig. 11. Left: Clover and Right: Cluster Ge detector designs.

The Euroball array consisted of 30 large volume germanium detectors (similar to Gammasphere), 26 Clover germanium detectors and 15 Cluster germanium detectors each with an associated escape-suppression shield. This gave up to 239 individual Ge elements. The array had a total photopeak efficiency of ~10% at 1.3 MeV.

The first phase of Euroball began in early 1997 at Legnaro National Laboratories, Italy. Then in November 1998 Euroball was moved to the Institut de Recherches Subatomiques, Strasbourg, France and upgraded to include an inner BGO array consisting of 370 BGO detectors. The ball and the Ge detectors measured the total number of gamma rays emitted together with their total summed energy. Euroball IV commenced operations in June 1999 and ceased operations at the end of 2002. For further details on Euroball see

http://eballwww.in2p3.fr/EB/ .

However the detectors used in Euroball continue to perform world-class science and have been moved to a number of newer initiatives. These projects include RISING at GSI, Jurogam I and now Jurogam II at Jyväskylä, and CLARA-PRISMA at Legnaro.

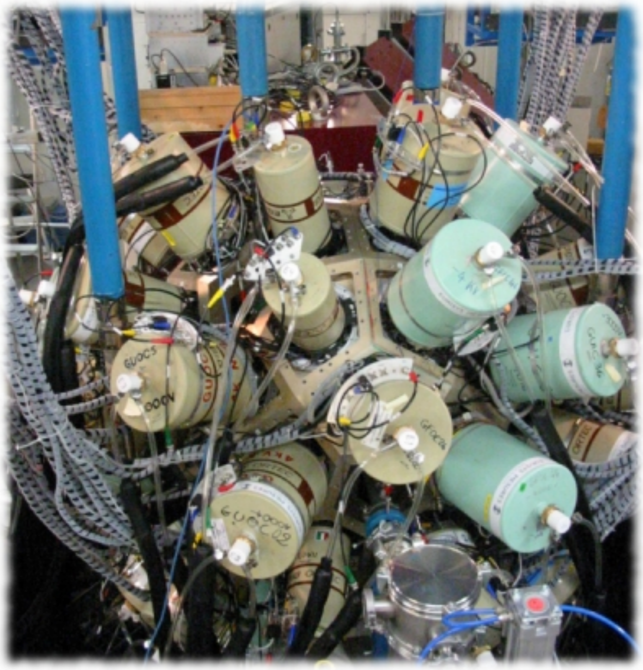

Fig. 12 JUROGAM I at Jyvaskyla.

JUROGAM is an array of escape-suppressed HPGe detectors for use at the target position of the RITU gas-filled recoil separator at the Accelarator Laboratory of the University of Jyvaskla. A variety of different detectors types have been used in assemblies this array and include Eurogam clover, Eurogam Phase I and GASP Ge detctors provided by the Euroball collaboration and the UK-France detector loan pool. The support structure and frame of the array are from the earlier implementations of Eurogam 1, which was situated at Daresbury Laboratory in the U.K., and Eurogam II at IReS Strasbourg in France. The total peak efficiency for Jurogam 1 (43 escape suppressed single Ge detectors) is 4.2% and is 6% for Jurogam 11 (15 single and 24 Clover escape suppressed spectrometers), for 1.3 MeV gamma rays.

For futher information see:
https://www.jyu.fi/fysiikka/en/research/accelerator/nucspec/jurogam

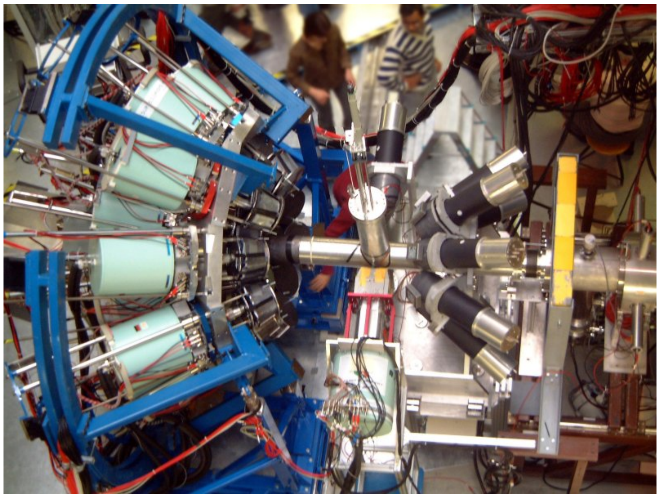

Fig. 13. RISING at GSI.

The RISING (Rare Isotope Spectroscopic Investigation at GSI) array is built from Euroball Cluster Ge-detectors. This array has been operated in several configurations. A “fast beam” set-up, as shown in Fig 13, specifically designed to maximize the efficiency following reactions with relativistic heavy ion beams. The Miniball triple cluster detectors were also added to this fast beam set-up. A “stopped beam” set-up was used with the 7 Clusters (105 Ge detectors) compactly arranged around a passive or active target to study the decay properties of exotic species selected by the FRS. A set-up for g-factor measurements was also used.

For more information on RISING see:
http://www-aix.gsi.de/~wolle/EB_at_GSI/main.html .

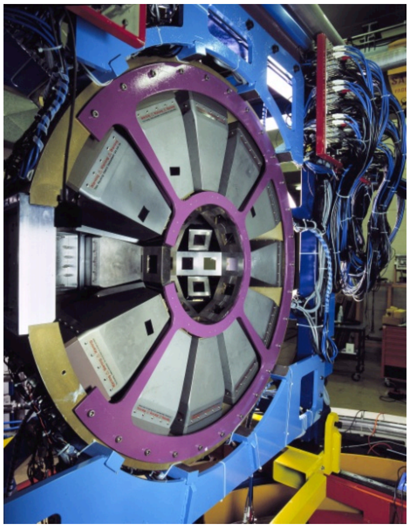

Fig. 14. The CLARA-PRISMA array at Legnaro.

The CLARA array is composed of 25 Clover detectors placed at the target position of the magnetic spectrometer PRISMA at Legnaro.

For further information see http://euroball.lnl.infn.it/EBcontents/EBweb_pdf/EBRW_10.pdf

Another mid-90's European 4π array was GASP, which consisted of 40 escape suppressed Ge detectors. This array ran successfully at Legnaro National Laboratory in Italy for many years. A new initiative using these detectors is the GALILEO array also at LNL. The GALILEO system will combine the GASP tapered detectors and European Gammapool Cluster detectors. The new array will take the original Euroball seven-element cluster detectors and put them into triple cluster detector modules. The latter will be placed at 90 deg. with respect to the beam axis and the GASP detectors will cover the forward and backward angles symmetrically. A large suite of auxiliary detector systems will be coupled to GALILEO.

4.5 Miniball

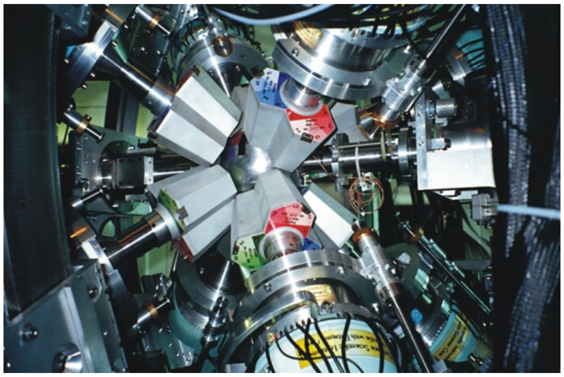

Fig. 15. MINIBALL at REX-ISOLDE/HIE-ISOLDE

The MINIBALL array is designed for low γ-ray multiplicity reactions using radioactive ion beams at the REX-ISOLDE facility at CERN. It consists of six-fold segmented, encapsulated Ge detectors.. The high segmentation allows useful Doppler correction of gamma rays emitted by fast moving nuclei. The 40 Ge detectors are arranged in eight cryostats with three detectors each and four with four detectors each. This arrangement provides optimal 4π Ge detector coverage making an absolute efficiency of 14% for MINIBALL at 1.3 MeV.

For further information see: http://cds.cern.ch/record/725972

4.6 EXOGAM

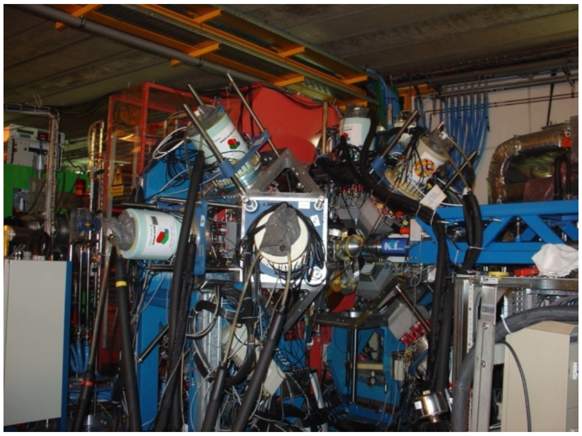

Fig. 16. EXOGAM at GANIL.

The EXOGAM spectrometer is a compact, flexible, high efficiency, highly segmented, array of 16 clover-type gamma-ray detectors This array was designed to optimize spectroscopic investigations using the exotic beams from the Systeme de Production d'Ions Radioactifs et d'Acceleration en Ligne (SPIRAL) facility at the Grand Accelerateur National d'Ions Lourds (GANIL) along with a suite of auxiliary devices and the high efficiency recoil spectrometer VAMOS. For further information see http://www.ganil-spiral2.eu/science-us/detection-system/detectors.

4.7 TIGRESS and GRIFFIN

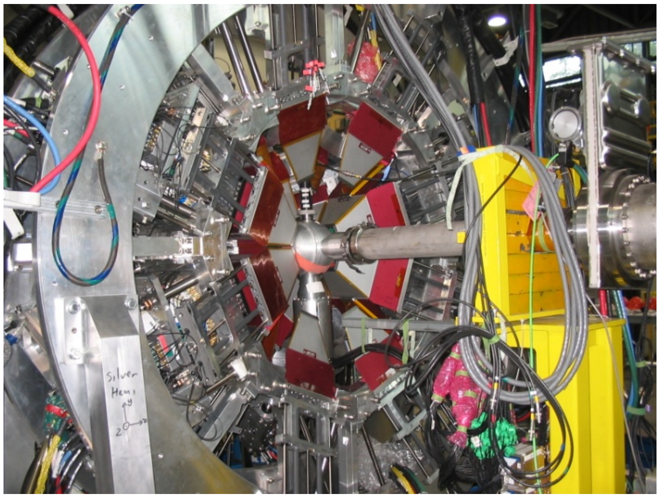

Fig. 17. The TIGRESS array at TRIUMF.

The TRIUMF-ISAC Gamma-Ray Escape Suppressed Spectrometer or TIGRESS, consists of up to sixteen 32-fold segmented Ge clover type detectors and an escape-suppression shield for use with exotic beams provided by the ISAC-II superconducting linear accelerator at TRIUMF. Like EXOGAM this array can be transformed into two modes; (i) high peak to total mode with the suppression shields surrounding the Ge Clover modules and (ii) high-efficiency mode in which the Ge Clover modules (without inter-Clover suppressors) are pushed forward to only 11 cm from the target. A suite of auxiliary systems are available for charged particle and neutron detection. A customized fully digital electronics data acquisition system is employed. For more information on TIGRESS see: http://www.physics.uoguelph.ca/Nucweb/tigress.html

A new and exciting initiative at TRIUMF is the GRIFFIN (Gamma-Ray Infrastructure For Fundamental Investigations of Nuclei) array for decay spectroscopy with low energy radioactive ion beams from the ISAC accelerator. GRIFFIN will consist of sixteen large Clover Ge detectors arranged in a close packed geometry to optimize efficiency. It's total photopeak efficiency being ~ 24% at 1 MeV. This means that GRIFFEN will be ~17 times more efficient than the 8π Spectrometer it will replace and thus ~300 more efficient for gamma-gamma coincidences. GRIFFIN is designed to be compatible with existing auxiliary detector systems of the 8π Spectrometer. The system will use customized digital electronics. GRIFFIN will its early implementation phase in 2014 and is expected to be fully operational in 2015. For further information see:
http://www.physics.uoguelph.ca/Nucweb/griffin.html

4.8 SeGA

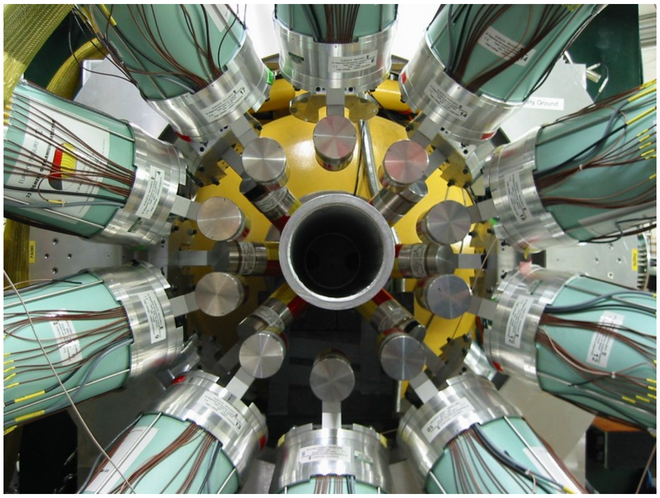

Fig. 18. The SeGA array at the National Superconducting Cyclotron Laboratory.

The Segmented Germanium Array (SeGA) is specially designed to perform high-resolution γ-ray spectroscopy of fast exotic beams from the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University. The array consists of eighteen Ge detectors (without escape suppression) each electronically divided into 32 segments. The segmentation, as with the other discussed systems, allows the gamma-ray hit information to be localized which helps enormously in reducing the uncertainty in the Doppler correction due to the finite opening angle of the detector. The detectors can be placed at various distances to optimize between efficiency and resolution tradeoffs. The normal setup gives a total photo peak efficiency of ~3% at 1.3 MeV. For further information on SeGA see: http://www.nscl.msu.edu/tech/devices/gammarayspectrometer .

4.9 CLARION

Fig. 19 The CLARION array at HRIBF at Oak Ridge National Laboratory.

The CLARION Ge array consists of eleven segmented Clover detectors and is situated on the Recoil Mass Separator beam line of the Holfield Radioactive Isotope Beam Facility (HRIBF) at the Oak Ridge National Laboratory. The Clovers can be placed a several distances from the target but at ~22 cm the array has a total photopeak efficiency of about ~2.4% at 1.33 MeV. For further information see: http://www.phy.ornl.gov/hribf/research/equipment/clarion/

4.10 INGA

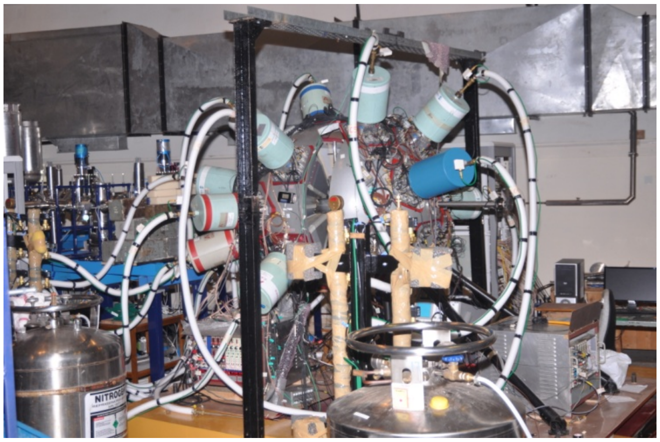

Fig. 20. The INGA array at the TIFR-BARC Pelletron-LINAC facility.

A large collaboration of Indian research institutions and universities has lead to the building of the Indian National Gamma Array (INGA). It is composed of up to 24 escape-suppressed Clover detectors and uses a full digital electronics data acquisition system. INGA has a total photo-peak efficiency of ~5% at 1.3 MeV. It is currently in use at the TIFR-BARC Pelletron-LINAC facility in Mumbai but will rotate between the other accelerator facilities within India, see http://www.tifr.res.in/~nsg/ for further information.

4.11 AFRODITE

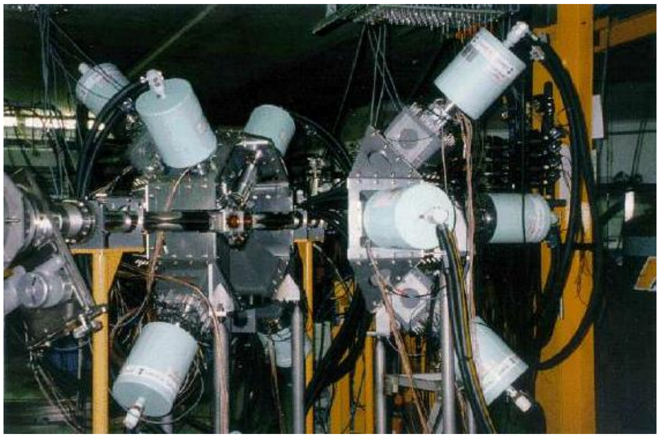

Fig. 21. The AFRODITE array at iThemba-LABS.

The AFRODITE array is situated at iThemba LABS in South Africa and is composed of 8 Clover detectors of Euroball design and 8 LEPS detectors. The latter provide exceptional efficiency for the detection of low energy photons (<100 keV). A digital electronics system upgrade has recently been implemented. A number of auxiliary detectors are available, for further information see http://www.tlabs.ac.za/nucafrodite.htm .

4.12 EURICA

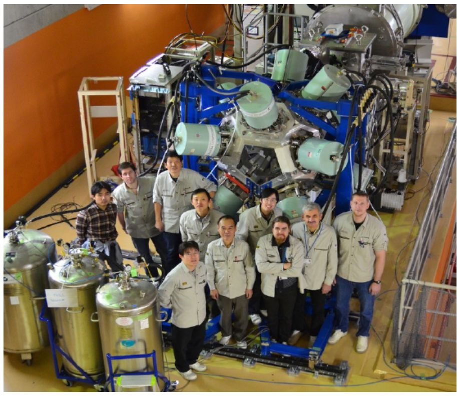

Fig. 22 The EURICA array at RIKEN.

The EURICA array at RIKEN (EUropean RIken Cluster Array) in Japan currently comprises 12 Cluster Ge detectors from the Euroball / RISING set-up. An additional 21 $LaBr_3$ detectors, from the proposed future FATIMA array, will be used to complement the 12 Cluster detectors with “fast-timing” coincidence capability from mid 2013. EURICA began operation in June 2012 and is scheduled to run decay and isomer spectroscopy experiments at RIKEN until the end of June 2014 using the projectile fragmentation and projectile fission secondary radioactive beams from the

RIBF facility, see http://www.riken.jp/engn/r-world/info/release/press/2012/120326_4/index.html .

4.13 Other Ge based arrays

A number of smaller or previous generation gamma-ray arrays continue to perform first class physics at many laboratories and institutions around the globe. It is not possible within this work to discuss all of these systems in detail but examples include; the CAESAR array at the Australian National University, the FSU Gamma-Array at Florida State University, the STARS-LIBERACE system at Lawrence Berkeley National Laboratory, the GEANIE array at Los Alamos National Laboratory, the ex-Yrastball array from Yale University which is now part of a mobile US Clover pool of detectors, the OSIRIS array in Warsaw, the 8 π array at TRIUMF, ORGAM at IPN Orsay, GABRIELA at Dubna, and in Japan, GRAPE, HyperBall 2 and GEMINI II.

5. Future Outlook

High resolution gamma-ray spectroscopy is one of the most powerful tools to study the structure of atomic nuclei and has seen many major advances in recent decades. It is a field that continues to reveal fascinating and often surprising new aspects of nuclei at the limits of isospin, excitation energy, angular momentum, temperature, and charge. The development of the next generation gamma-ray tracking arrays and their huge gains in sensitivity or resolving power, combined with new accelerator developments, assures a most exciting future for nuclear structure physics. One should also remember that the instrumentation and technical advances driven by this work, and the knowledge gained by those involved, is important in a wide range of applications. These advances impact areas such as medical imaging systems, homeland security, space exploration, and environmental monitoring.

Bibliography

[1] Lee, I.Y. and Simpson,J., (2010) AGATA and GRETA: The future of gamma-ray spectroscopy. Nucl. Phys. News Intl. 20, 23.
[2] Lee, I.Y., Deleplanque, M.A. and Vetter,K., (2003) Developments in large gamma-ray detector arrays. Rep. Prog. Phys.66, 1095
[3] J. Eberth, J. and Simpson, J., (2008) From Ge(Li) detectors to gamma-ray tracking arrays 50 years of gamma spectroscopy with germanium detectors. Progress in Particle and Nuclear Physics 60, 283.
[4] Sharpey-Schafer, J.F. and Simpson, J., (1988) Escape suppressed spectrometer arrays: A revolution in γ-ray spectroscopy. Progress in Particle and Nuclear Physics. 21, 293-400.
[5] Nolan, P.J., Beck, F.A. and Fossan, D.B. (1994) Large arrays of escape-suppressed gamma-ray detectors. Ann. Rev. Nuc. Part. Sci. 44 , 561-607.
[6] Simpson, J., et al., (1994) Multiple band terminations in ^{158}Er. Phys. Lett. B 327, 187.
[7] Paul, E.S., et al. (2007) The return of collective rotation in ^{157}Er and ^{158}Er at ultra-high spin. Phys. Rev. Lett. 98, 012501.
[8] Wang, X., et al., (2011) Quadrupole moments of collective structures at ultrahigh spin in ^{157}Er and ^{158}Er: A challenge for understanding triaxiality in nuclei . Phys. Lett. B 702, 127.