Executive summary

The continuous development of high-resolution gamma-ray detector systems has been of vital importance to nuclear structure physics. It has steadily expanded the limits of what can be observed and many new phenomena have been discovered, leading to unexpected insights into the nature of the atomic nucleus. Several germanium arrays have been built in the last decade and these have significantly contributed to such progress: the most efficient and sensitive being EUROBALL in Europe and GAMMASPHERE in the USA. The EUROBALL [1] array was initially operated at the Laboratori Nazionali di Legnaro, Italy (1997-98) and later at the Institut de Recherches Subatomiques, Strasbourg, France (1999-2003). During this period more than 110 experiments were performed involving ~400 scientists representing 24 countries and ~75 institutes.

EUROBALL was designed with the principle aim of carrying out studies of nuclei at very high angular momentum, close to the fission limit. During the Strasbourg phase of operation (i.e. EUROBALL IV[a]2 3) a Bismuth Germanate (BGO) calorimeter ("inner ball") was added to the array to assist with the investigation of these physics goals. The phenomenon of superdeformation, with its many fascinating properties, has been one of the major successes of this work. With the improved sensitivity of the new arrays it has been possible to study, in detail, the collective modes built on states at large deformation and to extend the concept of superdeformation to very light nuclei, where the elongated shapes are found to decay by both gamma ray and charged particle emission. The study of high spin states has also led to the discovery of new collective modes (wobbling motion) and of new symmetries (chirality) in nuclei, both of which are closely linked to a stable triaxial shape of the nuclear mean field.

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[a] The official name of the array has been EUROBALL III during the Legnaro phase and EUROBALL IV for the one in Strasbourg. This to stress the fact that EUROBALL is a development of previously existing devices and that it was continuously improved. The first phase of EUROBALL were the GASP spectrometer [2] in Legnaro and EUROGAM phase I in Daresbury [3], while the second phase of EUROBALL corresponds to EUROGAM phase II in Strasbourg [3].

EUROBALL has also been coupled to powerful "ancillary" detector systems, which have proved to be excellent instruments for exploring the properties of very exotic nuclei far from beta-stability. The ancillary detectors utilised include devices for the detection of light charged particles (ISIS [4], EUCLIDES [5] and DIAMANT [6]), neutrons (Neutron Wall [7]), evaporation residues (RFD) [8], fission fragments (SAPhIR) [9], binary reactions products (BRS) [10] and high-energy γ-rays (HECTOR) [11]. A large fraction of the most recent EUROBALL experiments has exploited the isospin degree of freedom by studying both proton-rich and neutron-rich nuclei populated with very low cross-sections (down to a few hundred nb). These studies have allowed new facets of the nuclear effective force to be investigated.

The contruction of the EUROBALL array required important technical developments in Germanium detector technology to be pursued. The Ge CLOVER detector, first used in the EUROGAM II array, was the first example of a *composite detector,* where several Ge crystals are operated in the same cryostat. For the EUROBALL CLUSTER detector a new technology to *encapsulate the Germanium crystals* in a sealed aluminium can had to be developed. This technology is currently being utilised for Ge detectors on European space missions. The EUROBALL collaboration has subsequently designed the first *segmented Ge detectors*, which are now operated in the EXOGAM and MINIBALL spectrometers. In 1999, these developments led to the initiation of a further development programme for gamma-ray tracking detectors in Europe.

In this report the results obtained with EUROBALL are presented in a comprehensive way, together with an assessment of the technical merits of the array and reports on the ancillary detectors that were built for use with EUROBALL. Since many of the recently performed experiments are not yet fully analysed this document can only give a preliminary report on the achievements to date. In an annex information on the performed experiments, publications, and PhD thesis work is documented.

Superdeformation and other exotic shapes

The study of nuclear superdeformation has been one of the major successes of nuclear structure research in the last 15 years, since the discovery of the first superdeformed (SD) rotational band at high spin in ^{152}Dy. In this period more than 200 bands have been studied in many different regions of the Segrè chart (A~30, 60, 80, 130, 150, 160, 190 and 240). The large amount of experimental data collected, which began with the previous generation γ-arrays, have provided a continuous challenge to mean field theories aiming to explain the properties of nuclei in these very elongated shapes. Unexpected and sometimes surprising properties of superdeformed nuclei were found, but many open questions remained to be answered. The results obtained from EUROBALL will be discussed in detail in Section 1 ("Nuclei at very elongated shapes").

EUROBALL with its high resolving power, large efficiency and innovative additional detectors, especially the INNER BALL calorimeter, has brought new information on some of the most surprising phenomena observed in superdeformed nuclei, e.g. the observation of "identical bands" and very small regular oscillations in the moments of inertia ("ΔI=4 staggering"). Other highlights are the final proof of the existence of octupole vibrations, an elementary excitation mode built on the superdeformed shape and the extraction of the neutron pairing gap in the second well of the Nd isotopes. The results on the octupole vibration in the second minimum were obtained by utilising the EUROBALL Clover detectors as Compton polarimeters in order to measure the linear polarisation of gamma rays, and hence their electric or magnetic character.

One of the main achievements in this field has been the discovery of a new region of superdeformed nuclei with stable triaxial deformation in the Lu and Hf isotopes around mass A=170 (cf. Section 2, "Strongly deformed triaxial nuclei"). These results have provided the first experimental proof for the existence of the "wobbling mode", a collective motion characteristic of a triaxial shape, which was predicted more than 25 years ago. It has also been shown in ^{154}Er, for example, that superdeformed structures with both prolate and triaxial shapes can coexist at high spin. This observation has allowed the resolution of long-standing difficulties in the theoretical interpretation of superdeformation in the A=150 mass region.

Large efforts have also gone into the search for hyperdeformed nuclear shapes, but undeniable evidence for such very strongly prolate deformed nuclei with an axis ratio of 3:1 remains elusive. On the other hand we have siginficantly improved our understanding of the experimental conditions needed in order to populate nuclei at extreme spin values, well in excess of $70\hbar$, where hyperdeformed nuclei are expected to be formed. A successful search for hyperdeformation may well be one of the prime examples, for which we will have to wait for the next generation of gamma-ray tracking spectrometers such as AGATA.

Rotational motion at finite temperature

The study of the rotational motion at finite temperature plays a crucial role in the understanding of the properties of the nuclear system beyond the mean-field description, providing relevant information on the two-body residual interaction responsible for the band mixing process. Many different studies related to the question of rotational motion at higher temperatures were performed with EUROBALL. These include the feeding and decay of superdeformed bands (cf. Section 3, "Population and decay from superdeformed states"), the investigation of the superdeformed quasi-continuum and the search for the Giant Dipole Resonance built on highly deformed nuclei (cf. Section 4, "Rotational motion in thermally excited nuclei").

The study of high lying excited states within a superdeformed well provides opportunities to investigate many intriguing nuclear structure aspects such as: the transition from ordered motion along the superdeformed yrast line to chaotic motion above it, perhaps through an ergodic regime; the robustness of collectivity with increasing excitation energy and spin and the largely-unexplored feeding mechanism of superdeformed bands. A very extensive study of superdeformed excited states has been carried out in ^{143}Eu and a clear picture of the feeding process in this nucleus is emerging. Concerning the decay-out, most bands are still not connected to the low-lying levels, because experiments are at the very limits of what present arrays can do. Here, the development of future gamma-ray tracking spectrometers will be vital. In the few cases where quantum numbers have been measured for superdeformed states, information on binding energies and pairing in the second minimum has been extracted as well as values for the interaction strength between superdeformed and normal-deformed states.

From experimental studies of the quasi-continuum we know at present that, in medium mass nuclei, already a few hundred keV in excitation energy above the yrast line rotational bands are close enough in energy to interact by residual interactions. In recent years, the study of rotational damping, i.e. the spreading of the electric quadrupole decay from a single state at spin I over a spectrum of final states all at spin I-2, has been focused on the dependence on nuclear mass and deformation. Several high-statistics EUROBALL experiments on normal-deformed nuclei in the mass region A~110 and of superdeformed nuclei in mass regions A~140 and 160 were performed and analysed using the fluctuation technique. The number of paths obtained by this analysis and their mass dependence is well reproduced by simulation calculations.

High spin physics and new modes of rotational motion

In the high-spin domain the phenomenon of terminating rotational bands is attracting much attention, since it relates the collective and single-particle properties of the nucleus. With the earlier arrays band termination had been extensively studied in the spin range 30-40ħ, limiting the experiments to nuclei with a rather small number of valence nucleons. With EUROBALL it became possible to extend these studies to much higher spins as discussed in Section 5 ("Pairing correlations and band termination at the highest spins").

Detailed spectroscopy in the spin range 50-60ħ has been performed for several Er isotopes. These studies have provided the first firm evidence for the demise of both proton and neutron static pairing correlations at ultra high spins. In addition, they have allowed important studies of abrupt band termination to be carried out in nuclei around the original classic band terminating nucleus ^{158}Er. Investigations of nuclei with A ~ 70 and 130 have also revealed new regions of "smoothly" terminating rotational bands, as well as providing the first hints of such behaviour in a highly deformed band of ^{132}Ce.

EUROBALL has also played an important role in disentangling the phenomenon of "magnetic rotation" (cf. Section 9), a new mode of nuclear excitation manifesting itself in regular bands in near-spherical nuclei where magnetic dipole transitions dominate the electric quadrupole decay. This phenomenon has now been established in several mass regions of near-spherical nuclei where high-spin orbitals are close to the Fermi surface. Magnetic rotation occurs when the symmetry of the nuclear system is broken by the current distributions of a few high-spin particles and holes outside a spherical or near-spherical core. If these currents lead to a large component of the magnetic moment vector perpendicular to the total angular momentum they generate strongly enhanced M1 radiation. In many cases data obtained with EUROBALL have allowed precise assignments to be made of the coupling of the relevant single-particle orbitals; lifetime measurements have also clearly proven a decrease of the M1 strength along the bands as expected from theoretical calculations.

The spectrometer has also been utilised to investigate chirality in nuclei. This phenomenon has been predicted in nuclei which have a stable deformed triaxial core and a few (1-2) valence nucleons occupying high spin particle and hole-like orbitals. Recent EUROBALL work, as well as studies in the USA, has revealed that odd-odd nuclei in the Rh region around mass 104 exhibit some of the nicest examples to date of chiral rotation in nuclei.

Physics near the *N*=*Z* line

The latest generation of large γ-ray spectrometers has boosted the exploration of nuclei under extreme conditions. Not only the limits of angular momentum and higher excitation energies have been approached, but the coupling of these instruments to selective ancillary devices has allowed for more and more refined investigations of the third important degree of freedom in contemporary nuclear structure studies, isospin. Near and along the line of nuclei with equal numbers of protons and neutrons (*N*=*Z)*, a reinforcement of shell structures occurs, since the neutrons and protons are filling identical orbitals and as a consequence their wave functions have a large spatial overlap. Spectroscopic studies of these nuclei enable the investigation of isospin $T = 0$ or $T = 1$ neutron-proton pairing correlations and their consequences. In particular, the knowledge of high-spin levels gives important information on a new superfluid phase of nuclear matter. In addition, the greatly improved or new experimental techniques have initiated a renaissance of interest in questions related to the isospin symmetry.

EUROBALL provided a breakthrough in the study of high spin states in *N*=*Z* nuclei. Here, the meaning of “high spin” is of course different to nuclei lying closer to the valley of stability, where spins in excess of $60\hbar$ can be reached in discrete spectroscopy. Because of the severe experimental difficulties encountered when studying heavy *N*~*Z* nuclei, states with spins of the order of $10\hbar$ are often considered as being “high spin”. A comprehensive summary of in-beam studies of exotic neutron-deficient nuclei in the vicinity of the *N*=*Z* line between ^{40}Ca and ^{100}Sn using the EUROBALL array is given in the Sections 6 and 7 of this report (“Symmetries in medium-light nuclei: at and beyond the *N*=*Z* line” and “Studies of *N*~*Z* nuclei beyond ^{56}Ni”). Highlights from these studies are new results on the isospin symmetry breaking in several *N*=*Z* nuclei, new or extended studies of mirror nuclei, shape changes in heavy *N*~*Z* nuclei and the approach to ^{100}Sn.

Nuclei on the neutron rich side of the valley of stability

Nuclei with an increased excess of neutrons as compared to the stable isotopes are even more difficult to access experimentally. Although often regarded as prime examples for the need of radioactive beam facilities, production methods with low-energy stable beams are available in limited form as spontaneous fission, fusion-fission or deep-inelastic reactions. These three classes of reactions have very different characteristics; both in the nuclei produced and in the angular momentum distribution achieved before γ-decay competes with neutron evaporation. They do, however, share some of the same practical difficulties, namely that in each event there are generally two product nuclei, and, that there are many possible products from any given choice of reaction or spontaneously-fissioning source.

In fission reactions there is an especially wide range of possible products - typical yields for a given isotope are of the order of 1% of the total - but tend to be much lower for the more exotic species. For this reason, the identification of data with a particular fragment requires exceptional selectivity, either through the use of high-fold γ data as available with EUROBALL, where it is a set of energies of coincident γ rays that uniquely identifies the product, or by the direct measurement of Z and A of one or both of the reaction products. In spite of these difficulties great progress has been made in the study of neutron-rich nuclei since the introduction of large arrays of Compton-suppressed Ge detectors as summarised in Section 0 of this report ("Nuclei on the neutron-rich side of stability"). New excited states in many isotopes have been identified and spectacular progress has been made in the techniques to measure spins, parities, lifetimes and even g-factors. As an example, new results obtained for several odd-proton isotopic chains, i.e. Tc, Rh, and In, has led to a better understanding of the properties of the proton single particle structure far from stability.

The powerful EUROBALL array is also a perfectly suited tool to unfold very complex gamma coincidence spectra arising from many nuclei produced in deep-inelastic heavy-ion reactions. The available quality and statistics of the gamma coincidence data makes it possible to reach products with very small production cross-sections and thereby to access a more neutron-rich region of isotopes. For example, an investigation of excited states in some nuclei around ^{48}Ca was possible despite very low production yields for the nuclei of interest.

Future perspectives

The EUROBALL coordination committee took the decision to stop the operation of the spectrometer in its current form in April 2003, once the campaign at IReS Strasbourg has been completed. In future, the resources from the EUROBALL array will be made available to the European Nuclear Physics community for dedicated campaigns at accelerator laboratories offering unique new physics opportunities. This programme, which should serve the needs of the community for the near future, will be coordinated by a network pooling the European resources for γ-ray spectroscopy. The EUROBALL campaigns have clearly shown that, besides a powerful gamma-ray spectrometer, efficient and dedicated particle detectors or spectrometers are the decisive ingredients if information from weakly populated nuclei is to be investigated. In fact, for a few years to come, until radioactive ion beams from the emerging new facilities reach appropriate intensities, gamma-ray spectrometers operated at a high intensity stable beam facility will be competitive for many of these studies.

For the first two years (2003/2004) campaigns at three different accelerator laboratories are being planned. They will employ different parts of the EUROBALL spectrometer and can hence be performed in parallel. At the cyclotron laboratory of the University of Jyväskylä (Finland) 45 large-volume Ge detectors will be coupled to the gas-filled separator RITU to perform experiments on heavy exotic nuclei with an emphasis on the study of very heavy nuclei beyond Z=100. At the Legnaro National Laboratory (Italy) the EUROBALL Clover detectors will be coupled to the new PRISMA spectrometer in order to study neutron rich nuclei by means of multi-nucleon transfer and deep-inelastic reactions. The EUROBALL Cluster detectors will be used for the “Rare Isotope Investigations at GSI” (RISING), i.e. spectroscopic studies of relativistic energy beams provided by the SIS-FRS facility. On a longer timescale it is planned to construct more powerful arrays by integrating other resources such as the MINIBALL and EXOGAM spectrometers for experiments at GSI and GANIL/SPIRAL.

Although EUROBALL has enabled the studies of very rare nuclear phenomena to be carried out, i.e. at the level of $\sim 10^{-5}$ of the production cross-section in a heavy-ion reaction, the development of a new generation of even more powerful gamma-ray spectrometers is vital to make future progress as has been illustrated by this report. Further progress, beyond the capabilities of EUROBALL, however, requires a completely new detection concept. For this purpose all interactions of each γ ray must be characterised in order to perform a full "*gamma-ray tracking*". Utilising this concept will allow the construction of a *complete Germanium shell*, which will have unprecedented qualities in terms of sensitivity and efficiency. Gamma-ray tracking is based on highly segmented, position sensitive Ge detectors and digital pulse processing electronics. Today we are at a stage where a new collaboration is emerging in order to develop the Advanced Gamma Tracking Array (AGATA). This array will open a broad range of new physics opportunities in connection with the (existing and future) radioactive and intense stable beam accelerators.

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