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Some physics highlights from the EUROBALL spectrometer

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PACS. 21.10.-k Properties of nuclei; nuclear energy levels – 23.20.Lv γ transitions and level energies – 23.20.-g Electromagnetic transitions – 25.70.-z Low and intermediate energy heavy-ion reactions

Introduction

The latest generation of large γ-ray spectrometers, such as EUROBALL, has boosted the explorations of nuclei under extreme conditions especially at the limits of angular momentum and at finite temperatures. But the coupling of this instrument to very selective "ancillary" devices allows for more and more refined investigations of the third important degree of freedom in contemporary nuclear-structure studies, the isospin. This contribution summarises some of the recent highlights from the physics at EUROBALL obtained in some of the different areas of nuclear-structure research.

Physics near the N = Z Line

The study of nuclei far from stability at the extreme values of N/Z is one of the major incentives of the existing and projected radioactive ion-beam facilities around the world. By investigating such exotic species certain terms of the nuclear Hamiltonian can be viewed under a magnifying glass, which are otherwise difficult to access. Near and along the $N = Z$ line, a reinforcement of shell structures occurs, because neutrons and protons are filling identical orbitals and their wave functions have a large spatial overlap. Spectroscopic studies of these nuclei enable the investigation of isospin $T = 0$ and $T = 1$ neutron-proton pairing correlations and their effects. Finally, improved or new experimental techniques initiated a renaissance of the interest in questions related to the isospin symmetry.

A summary plot 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 fig. 1. Highlights from these studies are new results on the isospin symmetry breaking in several $N = Z$ nuclei, *e.g.*, ^{64}Ge [1], new or extended studies of mirror nuclei (*e.g.*, ^{50}Fe/^{50}Cr [2], ^{47}Cr/^{47}Vd [3]), particle emission from very deformed states [4], shape changes and drip line effects in heavy $N \sim Z$ nuclei [5] and the approach to ^{100}Sn, *i.e.* spectroscopic studies of the heaviest nuclei with $T_z = 1/2$ (^{95}Ag [6]) and $T_z = 1$ (^{98}Cd, ^{102}Sn) studied so far. A more general recent review of in-beam and decay work of $N \sim Z$ nuclei including results from EUROBALL can be found in [7].

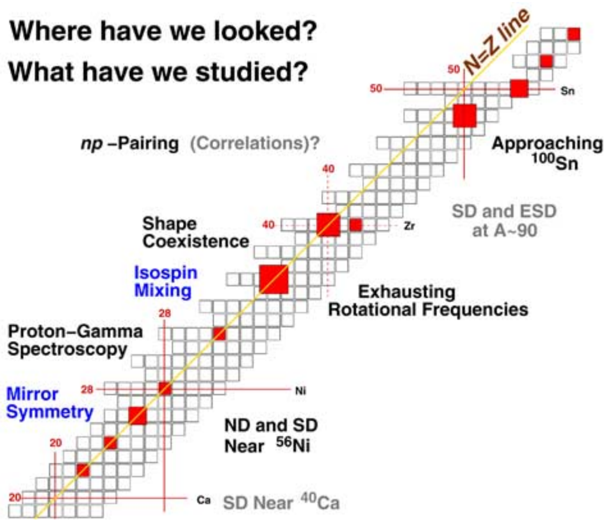

Fig. 1. Overview of topics covered with EUROBALL experiments aiming at nuclei beyond, at, or near the $N = Z$ line. Black squares indicate stable isotopes, gray squares denote the compound nuclei of the performed experiments. The size of such squares scales with the number of experiments (courtesy of D. Rudolph).

Besides a powerful gamma-ray spectrometer, efficient and dedicated ancillary devices for the detection of charged particles (ISIS [8] and EUCLIDES [9]), for neutrons (Neutron Wall [10]), or evaporation residues (Recoil Filter Detector (RFD) [11]), all of which have been

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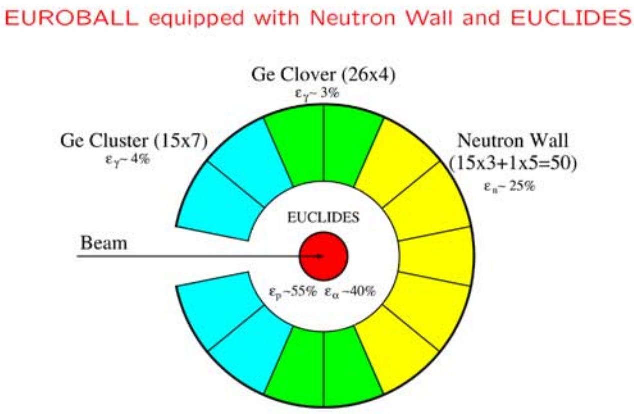

Fig. 2. Schematic view of the complex set-up to study the $T_z = 1$ neighbours of ^{100}Sn, combining an identification of the observed gamma rays through a measurement of evaporated particles (n, p, α) and tagging by isomeric decays (courtesy of J. Nyberg).

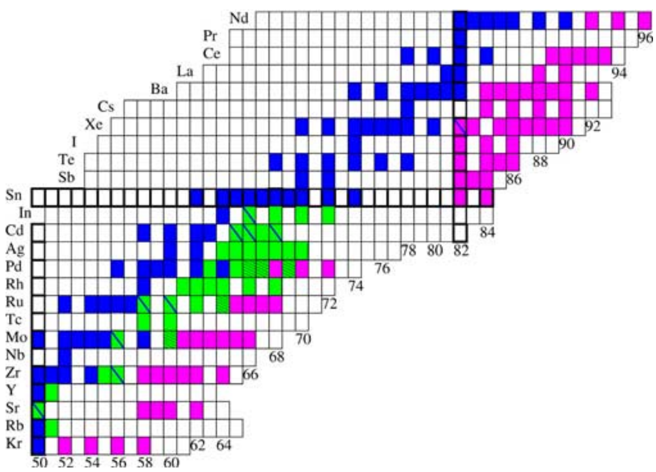

Fig. 3. Nuclei on the neutron-rich side of the valley of stability, which were produced and studied with the EUROBALL spectrometer using spontaneous and heavy-ion–induced fission reactions.

developed for EUROBALL, are decisive ingredients of the experimental set-up if information from such weak, exotic reaction channels shall be collected. As an example, the complex set-up used for the mass-100 study is shown in fig. 2, combining very successfully the advantages of light charged particle and neutron detection with the isomer tagging method.

New results on neutron-rich nuclei from fission studies

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 studies at 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 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, but they do share some of the same practical difficulties, namely 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. For this reason, the identification of data with a particular fragment requires exceptional selectivity, either through the use of high-fold γ data, 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 products.

In spite of these difficulties great progress has been made in the spectroscopy of fission fragments since the introduction of large arrays of Compton-suppressed Ge detectors. New excited states have been identified in many isotopes and spectacular progress has been made in the techniques to measure spins and parities, lifetimes [12,13] and even g-factors [14]. As one example, the new results obtained for several odd-proton isotopic chains, *i.e.* Tc [15], Rh, [16] and In [17] should be mentioned. Figure 3 summarises the nuclei studied with EUROBALL in recent years.

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 allows to reach products with very small production cross-sections and thereby to access a more neutron-rich region of isotopes. As an example a successful experiment was performed to study neutron-rich nuclei in the region of ^{48}Ca. Despite very low production yields for the nuclei of interest (less than 1% of the total reaction cross-section) investigation of excited states in some of the nuclei around ^{48}Ca was possible [18].

Superdeformation and other phenomena at very high spins

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. The large amount of experimental data collected with the previous-generation γ-arrays has been a continuous challenge to mean-field theories aiming at explaining the properties of nuclei in such an exotic shape. Some unexpected and surprising properties of SD nuclei were found (identical bands, oscillations of the moments of inertia), but many open questions still remained to be answered by the latest generation of γ-arrays such as EUROBALL. Among them the decay-out of SD bands and the presence of collective excitations (*i.e.* octupole modes) in the second minimum should be mentioned.

EUROBALL with its high resolving power, large efficiency and innovative additional detectors, especially the inner-ball calorimeter, has brought new information on the identical bands and staggering effects phenomena in SD nuclei; it has definitely proved the existence of an elementary mode of excitation, the octupole vibration, built on the SD minimum [19,20]. By identifying the very weak transitions connecting the SD band to the low-deformation states in ^{136}Nd it has allowed to extract the neutron pairing gap in the second well of the Nd isotopes [21]. The results on the octupole vibration in the second minimum are due to the unique capability of EUROBALL to measure the linear polarisation of γ-rays (and therefore of their magnetic or electric character) by means of the CLOVER germanium detectors used as Compton polarimeters.

One of the main achievement in this field has been the discovery of a new region of SD nuclei with stable triaxial deformation in Lu and Hf isotopes around mass $A \sim 170$ (cf. G.B. Hagemann, this issue, p. 183). This has allowed to prove experimentally the existence of the "wobbling mode" [22], a collective motion characteristic of a triaxial shape, predicted more than 25 years ago and never realised before in experimental high-spin spectra. Furthermore, it has been proven that SD structures at prolate and triaxial shapes coexist at high spin in the nucleus ^{154}Er [23], thereby resolving a long-standing difficulty in the theoretical interpretation of superdeformation in the mass $A = 150$ region.

In the high-spin domain the phenomenon of terminating rotational bands is attracting strong attention, since it relates the collective and single-particle properties of the nucleus. With the earlier arrays band termination has been extensively studied in the spin range 30–40$\hbar$, limiting the experiments to nuclei with a rather limited number of valence nucleons. With EUROBALL it became possible to extend these studies to much higher spins. In this way detailed spectroscopy in the spin range 50–60$\hbar$ was performed for several Er isotopes [24] and the first evidence for smooth band termination behaviour in the yrast highly deformed band in ^{132}Ce was revealed above spin 70$\hbar$ [25].

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. At present, we know that, in medium mass nuclei, already at few hundreds keV 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 $A \sim 110$ and of superdeformed nuclei in mass regions $A \sim 140$ and 160 were performed and analysed using the fluctuation technique (for a recent review see [27]). Other related studies are the search for the Giant Dipole Resonance built on highly deformed nuclei (cf. B. Million, this issue, p. 157), feeding and decay of SD bands (cf. A. Lopez-Martens, this issue, p. 49) and the investigation of the SD quasi-continuum.

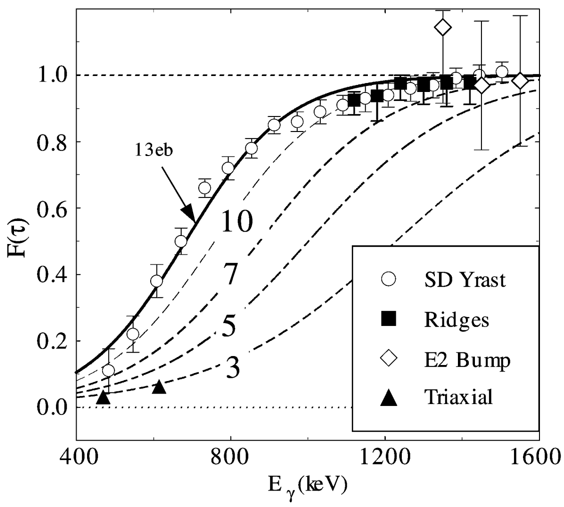

Fig. 4. Lifetime analysis of the SD ridges in ^{143}Eu showing that the higher-lying excited SD bands in this nucleus have the same deformation as the yrast SD band [26].

The superdeformed quasi-continuum has been extensively investigated with EUROBALL in the nucleus ^{143}Eu. Ridge structures with a spacing corresponding to the moment of inertia of the SD yrast states have been observed in the high transition energy region of γ-γ coincidence matrices, and for the first time a lifetime analysis based on the measurement of the fractional Doppler shift of the ridges has been performed [26]. As shown in fig. 4, the fractional Doppler shift $F(\tau)$ measured for the ridge structures (squares) is consistent with a quadrupole moment of $Q_{\mathrm{t}} \sim$ 10–13 eb, as obtained from the analysis of the SD yrast of ^{143}Eu, giving further support to the superdeformed nature of the unresolved discrete excited bands populating the ridges.

Perspectives

The EUROBALL spectrometer has now been in operation for more than 5 years, first in Italy at the Laboratori Nazionali di Legnaro (1997–1999), and since 1999 in France at the Institut de Recherches Subatomiques in Strasbourg. Recently, the EUROBALL Collaboration has decided that the resources of the spectrometer will be made available to the new *European Gamma-Ray Spectroscopy Pool*. From spring 2003 the European nuclear-physics community will perform dedicated experimental campaigns using the EUROBALL resources at accelerator laboratories offering unique new physics opportunities.

This will facilitate novel programmes in gamma-ray spectroscopy, such as the spectroscopic studies of very heavy and neutron-rich nuclei at the University of Jyväskylä, Finland and INFN Legnaro, Italy, respectively, as well as the Rare Isotope Spectroscopic Investigations at GSI.

On a longer time scale the European nuclear-physics community must investigate whether and how the EUROBALL Ge detectors can be best employed at new emerging (or planned) facilities for radioactive-ion and ultra-high–intensity stable beams. This may require the development of new digital electronics, but would make this very valuable resource attractive for many years to come in order to bridge the gap until the next-generation spectrometers, such as the Advanced Gamma Tracking Array (AGATA), will be available for experiments.

This contribution is based on the report *Achievements with the EUROBALL spectrometer* [28] which summarises (published and unpublished) results obtained in many different collaborations employing the EUROBALL spectrometer and its additional detectors. This report has been edited on behalf of the EUROBALL coordination committee from contributions by A. Bracco, R. Broda, R. Chapman, G. Hagemann, H. Hübel, S. Lenzi, A. Lopez-Martens, S. Leoni, E. Paul, M.-G. Porquet, D. Rudolph, J. Simpson, A.G. Smith, O. Stezowsiki, and R. Wadsworth, which were in part also presented at the EUROBALL symposium held in March 2002 at Orsay, France.

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