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Euroball: selected physics cases

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The Euroball γ-ray spectrometer resumed operation at the IReS-Strasbourg laboratory (Fr) in June 1999 after an eighteen months campaign at the INFN-Legnaro laboratory (It). Euroball is currently used to study the structure of atomic nuclei at extreme conditions of angular momentum and to address the physics of exotic and/or difficult-to-reach nuclei far from stability. A selection of physics cases and new results recently obtained with the spectrometer are discussed in this talk.

1. Introduction

During the last fifteen years, our understanding of nuclear structure was dramatically improved through the use of γ-ray spectroscopy. Atomic nuclei have proved to show a rich variety of phenomena when forced to the very limits of stability in terms of spin, isospin and mass. The observation of these phenomena, especially when their signatures manifested through electromagnetic decays are extremely weak, was only possible thanks to the construction of very efficient and sensitive γ-ray spectrometers such as Euroball in Europe [1] and Gammasphere in the USA [2]. These large multi-detector arrays and their predecessors, have pushed the observation limit in less than two decades by at least three orders of magnitude down to 10^{-5} of the production cross-section in a heavy-ion reaction. This current limit of observation is well illustrated by the recent measurement of one of the highest spin states ever observed (60 $\hbar$) in the yrast normal deformed sequence of ^{162}Er as shown in Figure 1 [3].

The Euroball collaboration (Denmark, France, Germany, Italy, Sweden, United Kingdom) was set up ten years ago to give physicists an opportunity of using a state-of-the-art Germanium (Ge) spectrometer with a total photopeak efficiency of the order of 9% at 1.3 MeV. The basic principle of operation is to efficiently collect high-fold coincidences from the long γ-rays cascades emitted by the decaying nuclei, in an array of Compton escape-suppressed Ge detectors. These data are then used to select from the reaction background extremely weak phenomena by imposing multiple-energy gates.

Euroball in its current phase IV comprises 71 detection groups of Ge and anti-Compton shields (a total of 239 single Ge crystals) that are distributed over the 4π solid angle of a spherical shaped geometry. Three types of Ge detectors are used: 30 large efficiency tapered crystals from the Eurogam 1 [4] and GaSp [5] arrays, 26 composite Clover detectors [6] from Eurogam 2 (four smaller coaxial crytals in a common cryostat) and 15 Euroball design Cluster composite detectors [7] (7 large efficiency encapsulated diodes in

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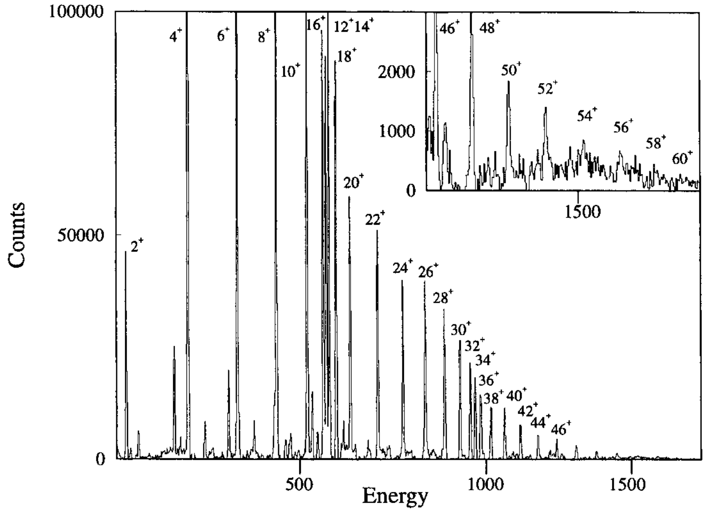

Figure 1. High-spin coincidence γ-spectra for the yrast band in ^{162}Er. A typical example of the quantum nuclear rotational spectrum from 0^+ to 60^+, interrupted by the first neutron ($i_{13/2}$) alignment at $I^\pi \approx 12^+$ and the first proton ($h_{11/2}$) alignment at $I^\pi \approx 34^+$.

a common cryostat).

The main feature of Euroball IV is the presence of an inner ball of BGO detectors (210 crystals). Altogether with the Ge detectors, they form a device of 164 equivalent detectors in terms of solid angle and efficiency allowing one to measure the γ-multiplicity and the sum energy, thus probing spin and excitation energy of a nuclear reaction. Such information constitutes a highly efficient filter to select specific reaction channels and to suppress unwanted background. These features make Euroball a unique tool used to address the physics of very high angular momenta, as for example: study of the highest spin states in normal deformed nuclei, structure of exotic nuclear shapes such as superdeformation with studies mainly focussed on the decay-out mechanism and the staggering effect, octupole correlations and hyperdeformation. In these structures, the purity of the single-particle configurations and (often) very weak pairing correlations make these systems a perfect laboratory to learn more about the exotic behaviour of the components of the nuclear force.

Now, moving to the next millennium, Euroball can be coupled with a full set of efficient ancillary detectors. They are used to increase the resolving power of the instrument by triggering on the light charged particles, neutrons, conversion electrons, recoil nuclei and fission or reaction fragments. An example of such an increase, through Doppler correction performed with the Recoil Filter Detector [8], is illustrated in Figure 2. Due to this essential increase in sensitivity, Euroball also became a powerful tool, able to perform

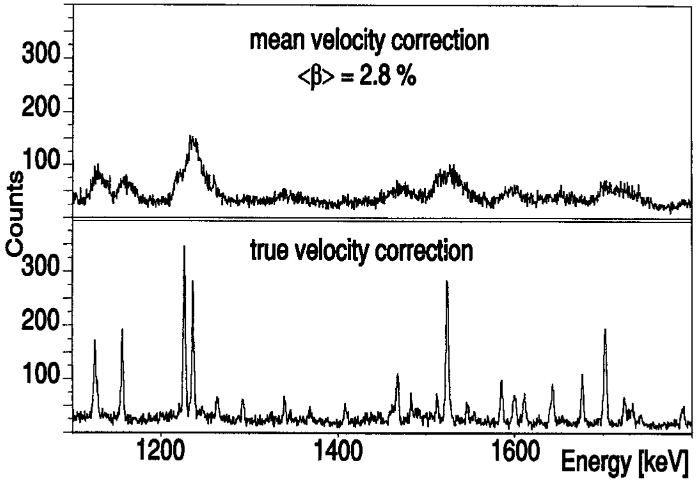

Figure 2. γ-spectra of a single cluster detector corrected for the true recoil velocity-vector measured with the Recoil Filter Detector for A=45 revealed significant reduction of Doppler broadening. The corrected γ-line width is 4 keV at 1.5 MeV.

detailled γ-spectroscopy of extremely weakly produced exotic nuclei lying far from the β-stability (nuclei close to those with N=Z from the $f_{7/2}$ shell up to A $\approx$ 100, neutron rich fission fragments) and very heavy isotopes in the transactinide region.

In this contribution some of the recent results obtained with Euroball will be presented based on experiments performed both in Legnaro and Strasbourg during the last three years. This selection could not avoid being subjective and only pretends to give a flavour of the physical case addressed by the Euroball community of users. Some other examples can be found as separate contributions to this conference.

2. ΔI=4 bifurcation in ^{150}Tb

The ΔI=4 bifurcation, also named staggering, is one of the few mechanisms which was not predicted theoretically and up to now is poorly understood. The idea to look for it in ^{150}Tb is to test the effect of the single-particle structure of superdeformed (SD) nuclei on the occurence of staggering of the dynamical moment of inertia $\mathcal{J}^{(2)}$.

This phenomena was first discovered in ^{149}Gd [9], where the dynamical moment $\mathcal{J}^{(2)}$ of the yrast SD band exhibits a small oscillation when plotted versus the rotational frequency of the nucleus. $\mathcal{J}^{(2)}$ is by definition inversely proportional to ΔE_γ, the energy difference between two consecutive members of the SD band cascade. In order to quantify this oscillation, it was suggested to subtract from this difference a smooth reference $\Delta E_\gamma^{\rm ref}$ [9] obtained by averaging over four consecutive transitions. This quantity $\delta(\Delta E_\gamma) = \Delta E_\gamma - \Delta E_\gamma^{\rm ref}$ is plotted in Figure 3. For ^{149}Gd (top left panel in Fig. 3) an oscillation of

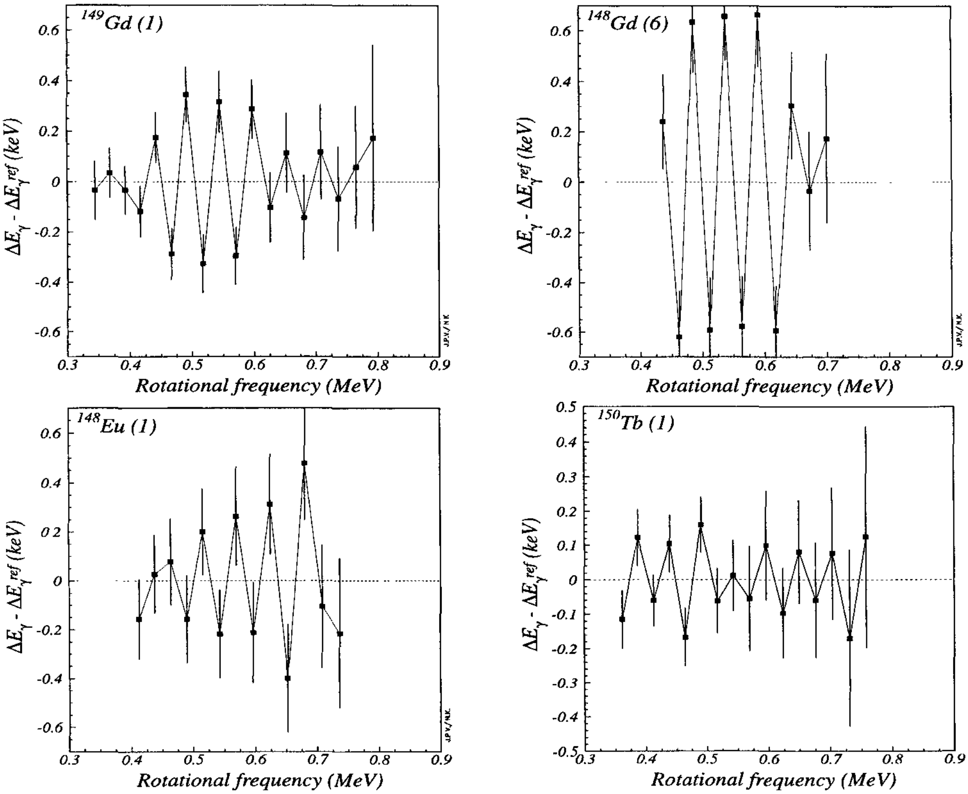

Figure 3. ΔI=4 bifurcation plots for the three "identical" SD bands observed in the mass A≈150 region with the intruder configuration of the SD yrast band of ^{149}Gd ($\pi 6^2 \otimes \nu 7^1$): ^{149}Gd(1),^{148}Gd(6) and ^{148}Eu(1). In the bottom right panel the new Euroball IV data for ^{150}Tb band 1 ($\pi 6^2 \otimes \nu 7^1$) are also displayed. Lines are drawn to guide the eyes.

the order of 0.2 keV in amplitude over a large frequency range from 0.4 MeV to 0.8 MeV is clearly visible.

This staggering effect corresponds to an alternating shift by a very small quantity upwards and downwards of the excitation energy of the nuclear states belonging to a rotational band. This produces two sequences of states with spins I,I+4,I+8, ... and I+2,I+6,I+10, ... In the case of ^{149}Gd the ΔI=2 displacement is about 60 eV at an excitation energy of 20 MeV corresponding to very small relative perturbation of the order of 10^{-6}.

Despite many theoretical attempts [10–14] to search for the physical origin of the staggering, there is no consensus. Among them, an attractive hypothesis is the C_{4v} point symmetry [10] for which a small term superposed with the axially symmetric nuclear hamiltonian can produce such an effect.

In the mass A≈150 region, the SD bands can be classified in terms of the single-particle occupation of intruder orbitals [15], so that the behaviour of the dynamical moments of the SD nuclei is nicely reproduced [16]. Starting from the ^{149}Gd core it was, therefore, interesting to check if the SD "identical" bands [17], i.e. bands with the same intruder configurations, exhibit the same kind of staggering effect.

The yrast SD band in ^{149}Gd, band 1, has two protons in the N=6 intruder orbital and one neutron in the N=7 intruder orbital leading to the SD configuration labelled $\pi 6^2 \otimes \nu 7^1$. Two other known SD bands have the same "identical" configuration: ^{148}Eu band 1 and ^{148}Gd band 6; both of them were investigated during the last few years at Gammasphere [18] while band 6 in ^{148}Gd was also studied with Eurogam II [19]. As shown in Figure 3, these two bands exhibit, over the same range of frequency a regular staggering pattern comparable to their "identical" reference band in ^{149}Gd.

Another attempt was to look for the occurence (or absence) and amplitude of the staggering of $\mathcal{J}^{(2)}$ when nucleons are added or removed from the ^{149}Gd core and to check separately the effect of the neutron and proton intruder orbitals. In ^{150}Gd for band 1, one more neutron occupies the signature-partner orbital N=7 leading to the $\pi 6^2 \otimes \nu 7^2$ configuration. This band does not show any staggering at all [20]. A possible explanation is that the staggering effect occurs only for the $\nu 7^1$ configuration and is cancelled if a second neutron occupies the $\nu 7^2$ orbital. In fact, it seems that this is a necessary but not a sufficient condition since for band 1 in ^{148}Gd which has the same intruder ^{149}Gd(1) configuration plus a hole in the [651] neutron orbital, there is also no evidence of a staggering effect. These results and the statistical analysis that was performed [20], support the existence of the ΔI=4 bifurcation phenomenon.

For the ^{150}Tb measurement, the idea was to modify the $\pi 6^2 \otimes \nu 7^1$ intruder configuration by adding a third proton in the N=6 intruder orbital and to look for a possible alteration of the staggering features. The experiment was performed by J.P. Vivien and collaborators at the IReS-Strasbourg laboratory, with the newly installed phase IV of Euroball. The SD bands in ^{150}Tb were populated in the ^{124}Sn(^{31}P,5n) reaction at a beam energy of 167 MeV. The trigger condition used to record data was that at least 4 Ge and 16 Inner Ball BGO elements fired simultaneously. In order to achieve an accuracy of about 0.2 keV precision for the measurement of the γ-ray energies, special techniques such as ellipsoidal gating and exact fold gating were used [21,22].

As shown in Figure 3, the dynamical moment of the yrast band in ^{150}Tb exhibits a regular staggering pattern but with a smaller amplitude as compared to the ^{149}Gd yrast SD band. A statistical analysis performed with the prescription of Ref.20, gives a significance (i.e. probability that a random distribution without any physical oscillation would produce a staggering pattern) of about 8% (about 2% for ^{149}Gd(1)). This still allows one to conclude the presence of the staggering effect in ^{150}Tb. Moreover, D.S. Haslip and collaborators [23] have shown, using the Hamamoto and Mottelson model [10], that magnitudes and phases of the staggering effect in neighbouring nuclei, may be viewed as correlated in a simple way with a cosine function, providing that the relative spin of the SD states are assumed [24]. The ^{150}Tb data also seem to be correlated with the three other cases in the mass A≈150 region [22].

This observation is really intriguing. As a provisional conclusion, I could say that there

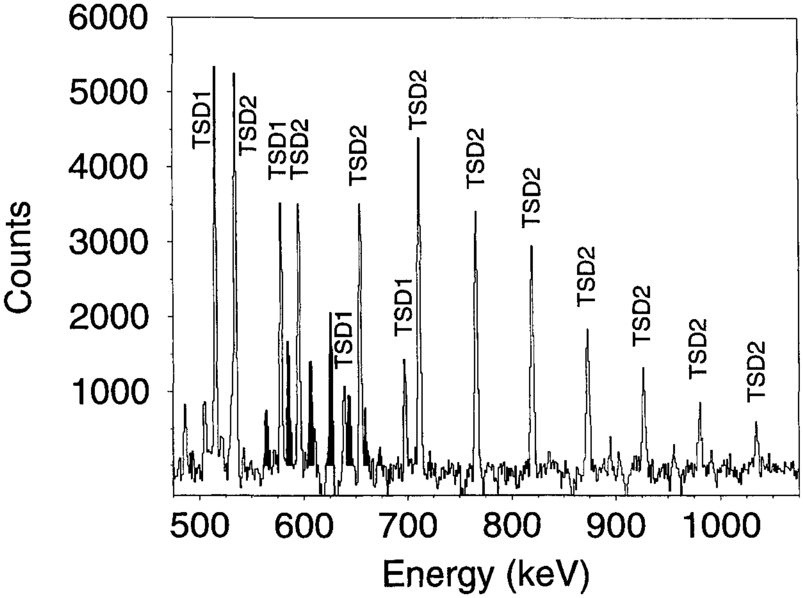

Figure 4. Connecting transitions between TSD1 and TSD2 (in black) as observed in the recent Euroball IV experiment that support the wobbling interpretation. This spectrum was obtained by double gating on selected TDS1 and TDS2 transitions.

is now definite and clear experimental evidence for four ΔI=4 bifurcation cases in the A≈150 mass region. Occupying a specific intruder orbital certainly has an influence on the staggering effect but is not simply the necessary condition for the occurence of the phenomenon.

Even if several theoretical explanations have been put forward, this extremely weak phenomenon is far from being understood and still remains an example in the superdeformed world of the nucleus where experiment is challenging theory.

3. Search for the Wobbling Mode

The wobbling mode is a direct and unique consequence of the rotational motion of non-axially shaped nuclei (i.e. all of the three principal axes have a different length). Predicted a long time ago by macroscopic model [25], it has so far never been clearly identified in nuclei. In that sense, it is just the opposite situation of the ΔI=4 bifurcation, observed but not predicted or explained.

In the high spin limit, an approximate expression for the excitation energies of the nucleus is:

$$E(I,n_w) = \frac{1}{2\mathcal{J}_x} I(I+1) + \hbar\omega_w(n_w + 1/2) \quad (1)$$

where $\mathcal{J}_x$ is the largest moment of inertia [25] (the main rotation axis is supposed to coincide with the x-axis). On top of the regular rotational bands, the wobbling degree of freedom introduces sequences of excited bands with an increasing number of wobbling quanta n_w. The spin is increased by 1 $\hbar$ for each phonon. A characteristic decay pattern is predicted that shows competition between the Δn_w=0 in-band decay transitions (stretched E_2) and the out-of-band decay Δn_w=1 (non-stretched $\Delta I = \pm 1\hbar$) E_2 interband transitions. The observation of these transitions and the measurement of the branching ratio, as discussed by Y.R. Shimizu and M. Matsuzaki [26], will provide an experimental signature of the wobbling motion.

Experimentally, favourable conditions to search for the wobbling mode may be given by nuclei in the region around N=94 and Z=71 for which highly deformed triaxial minima have been predicted by cranking calculations [27].

SD bands identified as triaxial bands (TSD) have been found in odd-proton ^{163,165,167}Lu isotopes [28–30] for which minima are calculated at $(\epsilon_2, \gamma) \approx (0.4, 20°)$. In a more recent experiment using Euroball III [31], a second excited TSD2 band has been observed in ^{163}Lu and the yrast TSD1 band built on the $\pi i_{13/2}$ orbital was considerably extended. The new TSD2 band was found to decay to the TSD1 band but no interband transitions could be firmly established.

In order to explore the possibility that this new band might be a wobbling band build on the yrast TSD1 band, a new experiment was performed by G. Hagemann and collaborators with Euroball IV to search for connecting transitions between the two bands. The TSD states in ^{163}Lu were populated via the ^{139}La(^{29}Si,5n) reaction at a bombarding energy of 152 MeV. The data analysis has revealed that TDS2 was connected to TSD1 by at least seven interband transitions as shown in Figure 4 [32]. The excitations energies of TSD2 and its relative population intensity versus TDS1, has allowed a tentative spin assigment for the states of TSD2. This assignment is fully compatible with interband transitions (ΔI=1 $\hbar$) characteristic of the wobbling mode decay pattern. A DCO analysis to determine experimentally the (mixed) multipolarity of these transitions is in progress.

Traditionally, the wobbling motion is supposed to be achieved at high angular momenta. The observed TSD bands are, in contrast, at relatively low angular momenta and are closely connected with the shell structure. This special feature of the wobbling mode was describe in Ref.33 and could be applied to the case of ^{163}Lu in which the high-j shell is the $\pi i_{13/2}$ orbital. The calculated branching to TSD1 is in qualitive agreement with observation.

Other explanations and the interpretation of TSD2 in terms of quasiparticle excitations can not be completely excluded so far: unfavoured $i_{13/2}$ signature-partner bands or negative-parity $h_{9/2}$ excited bands, but they are less probable because they are predicted to lie much higher in excitations energy realtive to TSD1 than is experimentally observed, and furthurmore, the expected branching from the $i_{13/2}$ signature partner is almost vanishing [32,33] in contrast to observation.

In the absence of other obvious explanation, these new Euroball IV data nicely support the interpretation of TSD2 as a wobbling excitation n_w=1 built on the $\pi i_{13/2}$ orbital so that ^{163}Lu appears as the first nucleus where evidence for the wobbling mode may have been observed.

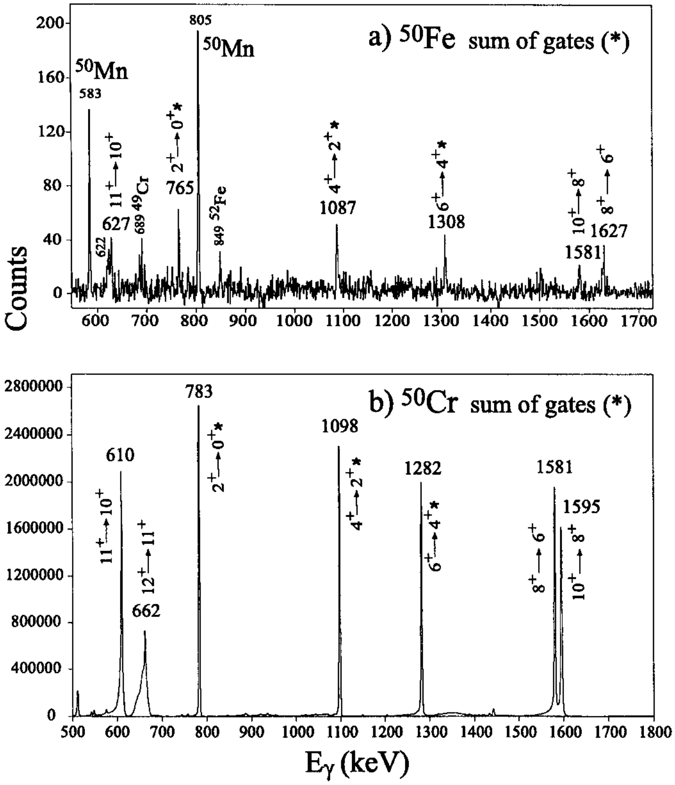

Figure 5. Gamma-ray transitions proposed to belong to ^{50}Fe, the heaviest T=1 (T_z=-1) nucleus ever observed, (top panel) as compared to the known rotational-like structure of the mirror nucleus ^{50}Cr (bottom panel)

4. Close to N=Z nuclei: from the $f_{7/2}$ shell up to A≈100

The study of nuclei far from β-stability close to the proton drip-line has become a major theme of research for the Euroball community. The use of ancillary detectors [34] such as Euclides (Si-ball) or the Neutron-wall coupled to Euroball allows the study of very exotic nuclei produced by stable beams with very low cross section. Almost 80% of the experiments performed with Euroball IV make now use of ancillary detectors.

The region of proton-rich nuclei close to N=Z, from the $f_{7/2}$ shell up to A≈100, is among the richest in terms of competing quantum effects. The experimental goals are varied and numerous. As an example, I could mention studies of shape coexistence between ND and SD with observable linking transitions or the proton emission from the second minimum as in ^{58}Cu that gives an additional control of the deformed mean field [35]. But there are also studies directly related to the specific structure of the N=Z nuclei such as enhanced proton-neutron (T=0) pairing, the violation of the isospin symmetry induced by the Coulomb interaction or the strong effect driven by the time-odd terms in the nuclear mean-field hamiltonian on the excitation energies that is predicted by Hartree-Fock calculations [36] and on which a forthcoming experiment in the vinicity of ^{32}S should shed light.

Some of the results obtained so far, see for example the first observation of excited states in ^{103}Sn [37] and the high-spin states observed in ^{64}Ge [38], are presented as separate contribution to this conference. The last part of my talk will be dedicated to the N=Z-2 ^{50}Fe nucleus for which the first identification of excited states was reported recently [39].

The ^{50}Fe nucleus lies in the middle of the $f_{7/2}$ shell, for which rotational-like structures have been reported up to very high spin for several nuclei [40]. Previous to this experiment, S. Lenzi and collaborators have reported on a rotational band in ^{50}Cr [41], the mirror nucleus of ^{50}Fe. This band presents a backbending around spin 8 $\hbar$, very well reproduced by full pf shell-model calculations [42]. The ^{50}Fe nucleus is the isobaric analogue of ^{50}Cr, two of the members of the A=50, T=1 isobaric triplet together with the ^{50}Mn nucleus.

The nucleus ^{50}Fe was produced in the reaction ^{28}Si(^{28}Si,α2n) at a bombarding energy of 110 MeV. Euroball III, reduced to Clover and Cluster germanium detectors, was coupled to the Neutron-wall (50 large volume detectors) and to the ISIS silicon ball (40 E-ΔE telescopes). Data were sorted in $\gamma - \gamma$ matrices in coincidence with charged particles and neutrons. Conditions were defined to accept candidate transitions belonging to ^{50}Fe: they have to be in coincidence with the neutrons, with only one alpha-particle and no proton. A weak rotational-like structure was found to fulfill those requirements. The gamma-spectrum is displayed in Figure 5, together with the relevant lines in the mirror ^{50}Cr nucleus that show backbending around spin 8 $\hbar$. The interpretation of this backbending in terms of particle alignment and pairing correlations, can be related to the Coulomb energy difference (CED) obtained by subtracting the corresponding level excitation energies of the two mirror nuclei. A theoretical interpretation of this CED is currently in progress.

5. Summary

Euroball IV has now been in operation for one year at the IReS-Strasbourg laboratory. First recent results of the Strasbourg and the Legnaro campaigns have been selected to highlight some of the Euroball physics case.

These results have demonstrated that Euroball is a very powerful γ-ray spectrometer in terms of limits of observation, that has been used to study nuclear structure at very high spin. Two opposite examples in the superdeformation world of the nucleus have been reviewed: ΔI=4 bifurcation in ^{150}Tb has confirmed the existence of this unforseen staggering phenomenon for which a theoretical explanation still remains unclear and the Wobbling Mode that may have been identified for the first time in the TSD bands of ^{163}Lu, supporting a 30-years old prediction.

But now, Euroball is even more powerful when coupled with ancillary detectors. These detectors allow one to select very weak reaction channels by triggering on light charged particle, neutrons, electrons, recoil nuclei, fission or reaction fragments. They are used to increase the array selectivity, to perform specific measurements and to apply various corrections (e.g. Doppler broadening corrections). With these detectors, Euroball also became a very efficient tool that is now used to address the physics of more exotic and/or difficult-to-reach nuclei far from β-stability. Several examples of results (e.g. ^{50}Fe) concerning nuclei close to those with N=Z have been presented at this Conference.

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