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Gamma decay of the GDR on superdeformed configurations of ^{143}Eu

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In this paper we discuss some relevant results of an experiment performed with the EUROBALL array equipped with large volume BaF_2 detectors in which coincidences between low-energy and high-energy γ-rays from the reaction ^{37}Cl (E_{beam}=165 MeV) + ^{110}Pd were measured. The main goal is to search for the giant dipole resonance built on superdeformed states and to determine the role played by the γ-decay of the GDR on the population of superdeformed configurations. The analysis of high-energy γ-ray spectra in coincidence with low-energy transitions of normal deformed and superdeformed types indicates the presence of the giant dipole resonance built on superdeformed states. Further support for this result is given by the analysis of the intensity of the superdeformed yrast and excited bands which is found to increase by a factor of approximately two when a coincidence with a high energy γ-ray is required.

1. INTRODUCTION

The focus of many experiments on nuclei with high angular momentum which were performed in the last years with large γ-detectors arrays has been the study of exotic nuclear shapes, particularly of superdeformed type and of the mechanisms leading to their population and decay out.

The problem of the population of superdeformed configurations has been one of the outstanding questions from the time of the discovery of the first superdeformed (SD) band [1,2]. In fact, it was a surprising result to find that superdeformed bands are populated with an intensity which is approximately one order of magnitude larger than that of normally deformed configurations at high spins. To explain this finding it has been proposed that the cooling of the residual nucleus by statistical E1 could be an important mechanism leading to the population of the superdeformed states [3]. This is because the E1 transition probability at $E_\gamma \approx$ 8-10 MeV for the decay of the giant dipole resonance (GDR) built on superdeformed configurations is expected to be larger than that of normal deformed states due to both the shape of the GDR strength function and to the level density of superdeformed states. In particular, for the GDR in a superdeformed nucleus one third of the total energy weighted sum rule strength (corresponding to the dipole oscillation along the nuclear symmetry axis of a collective superdeformed prolate nucleus) is at an energy close to the neutron binding energy and this is expected to favour the γ-decay of the GDR into a superdeformed state.

The attempts made in the last decade to find experimental evidence for the E1 feeding

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of superdeformed states did not give a conclusive answer to the problem mainly due to experimental limitations [4–6] of the set-ups used. It is clear from the existing work that to address this problem experimentally one needs to combine high resolution and high efficiency for the detection of low-energy transitions with the high-efficiency for the detection of the coincident high-energy γ-rays.

Recently, an experiment on ^{143}Eu has been made with the EUROBALL array, used to detect low-energy discrete lines, combined with 8 large volume BaF_2 detectors, used for the high-energy γ-rays. It was possible to obtain two types of spectra, one being the high-energy γ-ray spectra gated by selected transitions in ^{143}Eu and the other type being the spectra of the SD yrast and excited bands gated by high-energy γ-rays. The excited superdeformed bands of interest are those giving rise to the E2 bump in one dimensional spectra and to the ridge-valley structure in the $E_{\gamma_1} \times E_{\gamma_2}$ spectra similarly to what is seen in rotational normally deformed nuclei. In this experiment an Au backed target was used and in this way it was possible to identify the ridge structure much better and to measure for the first time its lifetime.

In the following, some of the relevant results concerning the search for the giant dipole resonance in superdeformed configurations and the role of the E1 decay in the feeding of superdeformed configurations are presented and discussed. A short description of the experiment is given in section 2 while the results concerning the high-energy γ-ray spectra are discussed in section 3. At last, the problem of the feeding is described in section 4 in three subsections, one concerning the yrast band, one the ridge structure and the third the rotational damped transitions of E2 type.

2. THE EXPERIMENT

The experiment was performed at the Laboratori Nazionali di Legnaro (Italy) where the EUROBALL array was placed. The measurements were made using a ^{37}Cl beam provided by the Tandem linear accelerator, at two bombarding energies, 165 and 170 MeV. The ^{110}Pd target (97.3% pure and 950 μg/cm^2 thick) had a Au backing of 30 mg/cm^2. The target backing was employed because we plan with this data set also to study the lifetimes of the E2 quasi continuum using the DSAM technique. For the beam energy of 165 MeV, whose data are presented here, the compound nucleus ^{147}Eu was formed at an excitation energy of 79 MeV. The maximum angular momentum is predicted to be 62$\hbar$ by the Swiatecki model [7] and 68 $\hbar$ by the model of Winther, in which the excitation of collective modes is taken into account in the formation process [8]. The total population of the ^{143}Eu residual nucleus was $\approx$70%.

The experimental apparatus used was a particular configuration of the EUROBALL detector array in which the tapered Ge detectors covering the front π of the array were removed and replaced by the 8 large volume BaF_2 detectors of the HECTOR array. With these scintillator detectors the high-energy γ-rays were measured in coincidence with low-energy transitions detected in the Ge detectors. The BaF_2 detectors had their front face at 30 cm from the target center and were shielded by lead to attenuate the low-energy γ-rays which, having larger multiplicities, can produce pile up with high-energy γ-rays. In addition, 4 small BaF_2 detectors were placed in the array (with the front face at the outer surface of the target chamber) to measure the time of flight with good resolution, information needed to reject neutron events. The time of flight of the Ge detectors was also measured relative to the small BaF_2 detectors so that a very good time resolution ($\sim$ 8 ns) was obtained for the Ge time spectra. The gain of each big BaF_2 detector has been monitored continuously during the experiment using a LED source and small shifts were corrected during the off-line analysis. The calibration of the HPGe detectors was obtained using sources of ^{152}Eu and ^{60}Co while the large volume BaF_2 were calibrated using the 15.1 MeV gamma produced by the reaction $^{11}B + D \rightarrow {}^{12}C^* + n$. We collected enough data with this reaction to be able to study the response and the adding back features at high-energy γ rays for the Ge cluster and clover detectors of EUROBALL [9].

We have accumulated events containing coincidences among a high-energy γ-ray ($E_\gamma >$ 3 MeV) measured in the BaF_2 detectors and γ-rays detected in HPGe detectors with the condition that at least 3 Ge detectors (without Compton suppression) had fired. The average fold of Ge detectors was $\approx$ 3 and this has allowed to construct the high-energy γ-ray spectra with gates on two low-energy transitions.

3. THE GDR IN SUPERDEFORMED CONFIGURATIONS

To search for evidence of γ-decay of the GDR in superdeformed configurations, the ^{143}Eu nucleus was chosen because it has some features that can be exploited for this purpose. In fact, this nucleus is characterized by a very intense continuum of E2 type that was found to originate from superdeformed configurations and to have a decay path feeding only selected intense low-spin states [10,11]. At low spins, due to the coexistence of both spherical (ND) and triaxially deformed (TD) shapes [12,13] this nucleus has a very complex and irregular level scheme while it becomes superdeformed (SD) at high spins [14, 15]. Both the superdeformed yrast band and the excited superdeformed states of the E2 continuum follow decay routes leading to low spin states of the spherical shape only (ND) [10,14,15]. This is consistent with the fact that the barrier between the superdeformed and triaxial energy potential minima is larger than the barrier between the superdeformed and spherical minima [12]. It is therefore expected that one should find evidence for the γ-decay of the GDR built on superdeformed states, not only in a more direct way, namely by gating with transitions of the superdeformed yrast band but also by comparing the high energy spectrum gated by low spin transitions of the spherical shape (populated by transitions from superdeformed states, and therefore collecting the entire superdeformed flux) with the spectrum gated by low spin transitions of the triaxial shape (not populated by the superdeformed states).

The two high-energy γ-ray spectra, one gated by spherical transitions and the other by triaxial transitions are shown in the left panel of figure 1. They are normalized at E_γ = 5 MeV. From this figure it is clear that, even with this rather efficient experimental array, it is not possible to measure the γ-decay from the high energy component of the superdeformed GDR strength function expected in the region at $\approx$ 18 MeV. One can note that the spectral shape and intensity is different in the region $8 < E_\gamma < 12$ MeV, where one expects to find the low energy component of the strength function of the GDR in a superdeformed nucleus. In fact, according to the hydrodynamical model, this low energy component should be at $\approx$ 10 MeV for a nucleus with quadrupole deformation with parameter $\beta \approx 0.6$, as in the ^{143}Eu case.

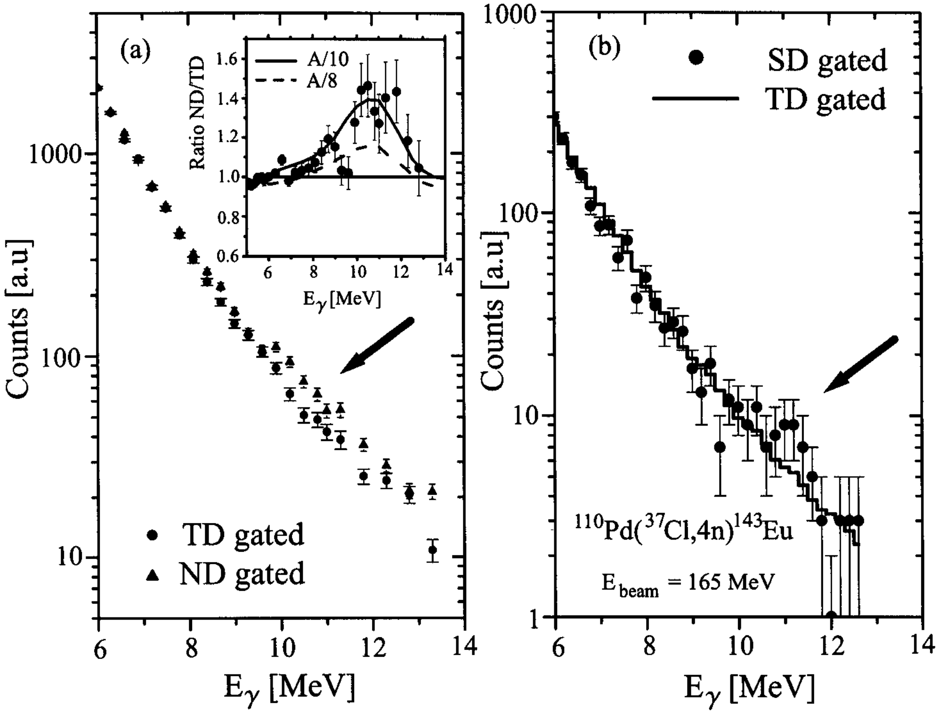

Figure 1. Left panel: The spectrum shown with filled triangles is double gated by two spherical transitions (populated by the SD decay); the other (filled circles) is double gated by the low-energy transitions of the triaxial configuration. In the inset the ratio spectrum obtained by dividing the two spectra is shown. The corresponding calculated values using the statistical model are shown with the lines. The dashed curve was calculated using a = A/8 MeV^{-1} for the level density parameter of all states, while the full drawn line curve was obtained using the value a = A/10 MeV^{-1} for the superdeformed states and a = A/8 MeV^{-1} for the normal deformed states. Right panel: Comparison of the high-energy γ-ray spectrum double gated by the lines of the superdeformed yrast band (filled circles) with the spectrum gated by lines of the triaxial configuration.

The interpretation of the excess yield seen in the high-energy spectrum gated by spherical transition as due to the superdeformed contribution can be verified by comparing the high-energy spectrum directly gated by the superdeformed transitions of the yrast band with the spectrum gated by the TD transitions. In the right panel of figure 1 these two spectra are shown. The spectrum gated by the SD yrast has been obtained requiring a double gate on two of any transitions of the band. It is possible to identify also in this case, in spite of the rather poor statistics, an excess yield in the region around 10 MeV, similar to that seen in the spectrum gated by the spherical lines populated by the decay of superdeformed configurations (cf. Fig. 1a), supporting its superdeformed nature.

It is interesting to examine the ratio of the high-energy spectrum gated by the ND transitions with that gated by TD transitions. This ratio is shown in the inset of figure 1. As one can see, the ratio is approximately 1 up to $E_\gamma \approx 8$ MeV while at larger γ-ray energies it deviates from 1 and shows a well defined excess centered at 10.5 MeV with a rather narrow width (of the order of 3 MeV). The excess of intensity observed is rather small (on average 20% in the region at E_γ = 8-12 MeV), and in general agreement with a previous explorative experiment [16]. This excess is expected to reflect the size of the region of the phase-space in which the superdeformation exists with respect to the total phase-space available. In order to understand this point on a more quantitative level simple statistical model calculations for this ratio spectrum were made. The calculation of the full decay cascades shown in the inset of figure 1 assumed a GDR of superdeformed type only at angular momentum $40\hbar < I < 55\hbar$ and energy U above yrast in the interval 0<U<15 MeV and with approximately 40 % of the total decay flux, as in ref. [10]. The GDR strength function was taken as a double Lorentzian with $E_{1GDR} = 10.5$ MeV, $\Gamma_{1GDR} = 3$ MeV with 33 % of EWSR strength and $E_{2GDR} = 17$ MeV, $\Gamma_{2GDR} = 6.5$ MeV with 66 % of EWSR strength. For the density of the superdeformed states we have assumed two different values (a=A/8 MeV^{-1}, and a=A/10 MeV^{-1}). The satisfactory description of the data obtained with these simple calculations leads to the conclusion that superdeformation is a property that the nucleus has only up to few MeV above the yrast line.

4. FEEDING OF SUPERDEFORMED CONFIGURATIONS

The effect of the E1 population of the yrast superdeformed band by the γ-decay of the giant dipole resonance built on a superdeformed nucleus is investigated by measuring the relative intensity of the SD band, of the ridge structure and of the E2 bump at different values of the energy of the gating high-energy γ-rays.

4.1. Feeding of the yrast band

The transitions of the superdeformed yrast band were identified in the spectra obtained starting from a γ-γ matrix gated by high-energy γ-rays measured in the BaF_2 scintillator detectors and for which the known Doppler corrections for the superdeformed band [17] has been applied on event-by-event basis. In the case of $E_\gamma > 6$ MeV (corresponding to the average value of $E_\gamma = 7.3$ MeV), the statistics is largely reduced but still the discrete transitions of interest are unambiguously identified. The intensity population of the yrast band has been determined using as a reference the 917 keV low lying spherical transition. The present results are shown in figure 2 together with a calculation of the ratio of the strength function of the superdeformed GDR ($E_{1GDR} = 10.5$ MeV, $\Gamma_{1GDR} = 3$ MeV with 33 % of EWSR strength and $E_{2GDR} = 17$ MeV, $\Gamma_{2GDR} = 6.5$ MeV with 66 % of EWSR) with the spherical GDR ($E_{GDR} = 14.5$ MeV, $\Gamma_{GDR} = 5$ MeV, 100% of EWSR), normalized to the data at 3 MeV. One can see that the population of the superdeformed band relative to that measured at $E_\gamma = 3$ MeV is found to be almost a factor of 2 larger when gating with $E_\gamma > 6$ MeV and follows remarkably well the simple estimates based on the shape of the E1 tail in a superdeformed nucleus.

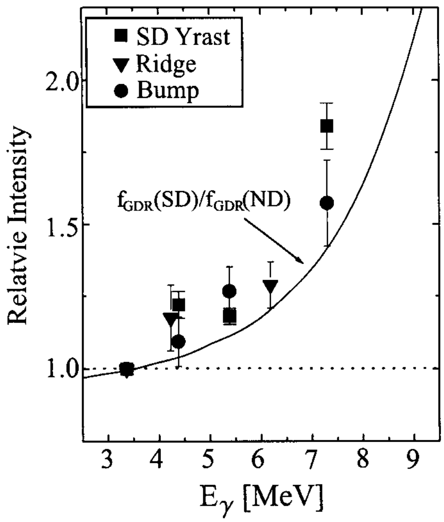

Figure 2. Intensity of the SD Yrast band (squares), of the ridges (triangles) and of the E2 bump (circles), as a function of the energy of the gating transition, normalized at 3 MeV. The full drawn line represents the ratio between the superdeformed GDR strength function and the spherical one, giving the lower limit for the feeding of a SD nucleus by El-decay from the GDR.

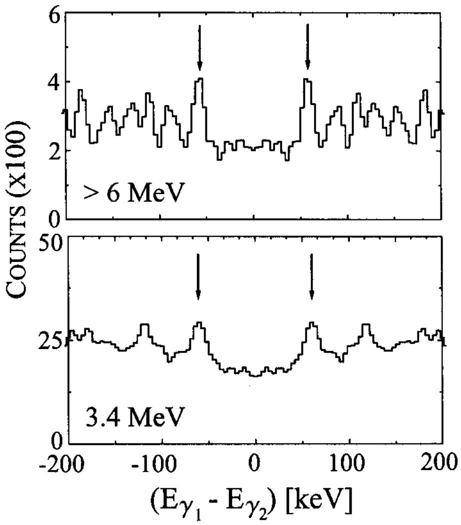

Figure 3. One dimensional projection on a 60 keV wide strip perpendicular to the main diagonal of the $E_{\gamma_1} \times E_{\gamma_2}$ spectrum. The average transition energy is 1140 keV. The spectrum in the bottom part is gated by high energy transitions with $E_\gamma = 3.4$ MeV while that in the top panel is gated by transitions with $E_\gamma \geq 6$ MeV.

4.2. The population of the ridge structure

As previously discussed, the nucleus ^{143}Eu is characterized by the presence of a rather pronounced ridge structure with a spacing corresponding to a moment of inertia with values similar to those of the yrast superdefomed band [10,11].

In contrast to the case of normally deformed nuclei, the ridge structure in this nucleus was identified only in a more limited region of spin. This was found to be due mainly to the fact that at low spin this nucleus has a very irregular level scheme with many transitions with energies falling in the region of the ridge structure and therefore covering a part of the region of interest. In the present experiment with EUROBALL, by using a Au backed target we were able to extend significantly the region in the $E_{\gamma_1} \times E_{\gamma_2}$ in which the ridge structure was clearly identified. In addition, the decay-out of these excited bands could be investigated [18].

The intensity of the ridge structure has been measured in coincidence with high-energy γ-rays. As one can see in figure 3, although the statistics is sensibly reduced, one can identify the ridge structure also when a coincidence with $E_\gamma \geq 6$ MeV is required and one

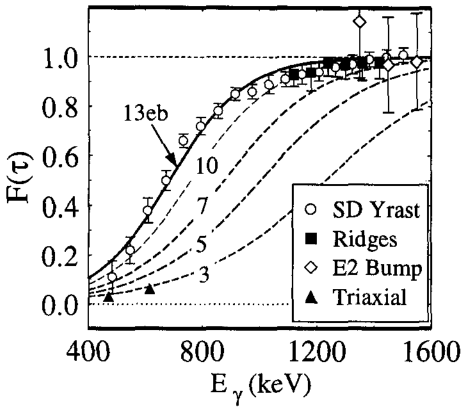

Figure 4. Doppler shift deduced for the ridge structure measured in the present data (filled squares) in comparison with the measurements for the SD yrast line (open circles) of ref [17], of the E2 bump [10] (open diamond) and of the triaxial transitions (filled triangles) [12]. The curves are from ref [17].

can also see that the ridge intensity is higher in the latter case. This behaviour similar to that found for the SD yrast line gives further support to the superdeformed nature of the ridge structure.

For the first time the lifetimes of the superdeformed ridges were also obtained with this experiment [18]. The corresponding results for the fractional shifts are shown in figure 4 in comparison with those of the superdeformed yrast bands. These two results, one concerning the feeding and the other the lifetime of the ridge structures, consistently indicate that indeed the ridge structure of the ^{143}Eu nucleus is formed by unresolved transitions of excited rotational bands of superdeformed nature.

4.3. Feeding of the E2 bump

As discussed in section 3 the nucleus ^{143}Eu was found to have a very intense continuum made of unresolved transitions of rotational type with damped character, similar to those seen in several normally deformed nuclei (cf. eg. [19]). In the case of ^{143}Eu the measurement of the angular distribution, of the moment of inertia and of the fractional Doppler Shift all consistently support the superdeformed nature of the unresolved transitions forming the continuous bump in the 1D spectrum gated by spherical transitions, in region E_γ = 1000-1800 keV.

An interesting feature of this intense E2 continuum is that it is seen only in coincidence with transitions among levels of the low-spin spherical shape of this nucleus. In contrast, the intensity of the unresolved transitions in the same spectral region is substantially reduced in the case of the coincidence with transitions of the low-spin states of the triaxally deformed shape (shape which coexists with the spherical one). This feature can be seen in figure 5 where spectra obtained in the present experiment are shown.

Another way to determine the superdeformed character of these unresolved transitions is to investigate their feeding properties and to see whether or not the population intensity follows the same behavious of the yrast superdeformed band. In figure 5 the continuous E2 spectra are shown for coincidences with high-energy γ-rays with $3 \leq E_\gamma \leq 4$ MeV (bottom panel) and $E_\gamma \geq 6$ MeV (top panel). One can see an enhancement of the intensity (by approx 1.5 times) of this E2 continuum when it is fed by E1 transitions (the corresponding

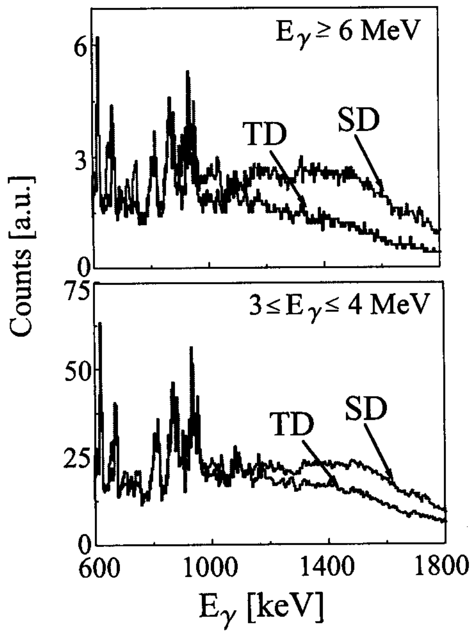

Figure 5. One dimensional spectra in coincidence with selected transitions of the nucleus ^{143}Eu. In the bottom part the spectra are measured in coincidence with high energy transitions with $3 \leq E_\gamma \leq 4$ MeV while in the top panel the spectra are those in coincidence with $E_\gamma \geq 6$ MeV transitions.

values of the intensity are plotted in figure 2).This result not only supports the presence of the GDR in the excited superdeformed nucleus but also gives another independent confirmation of the superdeformed nature of the E2 bump.

All the results concerning the feeding of the yrast, ridges and E2 bump consistently show the important role of the GDR built on superdeformed states.

5. SUMMARY AND CONCLUSIONS

In this work the problem of superdeformation at increasing excitation energy, starting from the yrast band, has been addressed in ^{143}Eu. For this purpose the γ-ray emission has been studied not only in the case of discrete transitions but also and mainly in the continuum region by investigating E2 ($E_\gamma = 1000-1800$ keV) and E1 ($E_\gamma = 3-15$ MeV) transitions. There are two relevant conclusions. The first is evidence for high-energy γ-rays emitted by the low component of the dipole vibration built on superdeformed configurations. The second is evidence for an enhanced feeding of the SD structure (yrast, ridge and rotational damped transitions) by E1 emission from the GDR built on SD states.

The combined study of the E2 emission from the collective regular and damped rotation and of the E1 emission of the giant dipole oscillation built on excited states have allowed substantial progress concerning the superdeformation problem at increasing excitation energy.

However, one needs to complete the picture investigating other mass regions also characterized by the presence of superdeformed shapes and this is part of the future program.

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