# EVIDENCE OF GDR ON SUPERDEFORMED $^{143}$Eu AND THE ROLE OF E1 EMISSION IN THE POPULATION OF SUPERDEFORMED STATES*

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High-energy gamma rays in coincidence with low-energy discrete transitions have been measured by coupling EUROBALL with the HECTOR array. The high-energy $\gamma$-ray spectrum in coincidence with superdeformed (SD) discrete transitions of $^{143}$Eu shows an 'excess' between 9-12 MeV if compared with the one associated to cascades which do not pass through the SD configurations. Such an 'excess' is in the energy region where one expects the low energy component of the GDR strength function built on a SD state. High energy $\gamma$-rays have been found also to enhance the population of the discrete SD band, the ridge structure and the superdeformed quasi-continuum showing that the E1 cooling is a preferred way to feed SD configurations.

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## 1. Introduction

The Giant Dipole Resonance (GDR) built on excited nuclei is an extremely powerful probe to study the structure of hot rotating nuclei. In fact, as the quadrupole degree of deformation strongly couples with the nuclear shape, by the measurement of GDR strength function it is possible to study the nuclear deformation and its temperature/spin induced dependence. The

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GDR properties have been measured, for example, as a function of excitation energy [1], angular momentum [2] or by choosing specific evaporation residues [3].

A still open and debated question concerns how cold superdeformed configurations are populated by the decaying compound nucleus. The feeding of superdeformed structures, in fact, has been a long-standing problem since the time of the discovery of the first superdeformed (SD) band [4,5]. In fact, it was experimentally observed 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. A possible explanation relies on the E1 statistical cooling [6, 7].

In the statistical model, the probability for a thermalized nucleus with excitation energy $E^*$ to emit a $\gamma$-ray of energy $E_\gamma$ is proportional to the product between the ratio of the level density of the final and initial state and the GDR strength function (see Eq. (1)) [8].

$$\frac{d\Gamma(E_\gamma)}{dE_\gamma} \propto E_\gamma^2 \frac{\rho(E_f^*)}{\rho(E_i^*)} \sigma_{\mathrm{GDR}}(E_\gamma) \,. \tag{1}$$

Because of the large deformation a superdeformed (SD) nucleus has, its GDR strength function is highly splitted and 33% of the Energy Weighted Sum Rule (EWSR) shifts from $\approx 15$ MeV to $\approx 10$–11 MeV. The left panel of figure 1 shows the GDR strength function in a spherical ($E_0 = 15$ MeV) and in the superdeformed case where 33% of the EWSR is shifted at 10.5 MeV and the remaining 66% at 17 MeV. Such highly splitted strength function will strongly enhance the E1 emission between 7–12 MeV if compared with the case of a spherical nucleus (see right panel of figure 1).

In medium heavy nuclei the particle binding energy ($E_{\mathrm{B}}$) lies between 8–11 MeV, (10.8 for $^{143}$Eu). Consequently, in a compound nucleus with an excitation energy comparable to its particle binding energy the $\gamma$ emission competes much more effectively with particle evaporation in a SD nucleus than in a spherical one, thus explaining the expected high yield in the population of superdeformed configurations relative to the normal deformed ones (see left panel of figure 1).

Experimentally it is a very difficult task to address this problem. In fact, one has to isolate and measure the cascades containing a high energy $\gamma$-ray ( $\approx 0.1\%$ of the cases) which end up in a superdeformed configuration ( $\approx 1\%$ of the cases). Consequently, the measurements of a GDR built on a SD state requires an experimental sensitivity of the order of $10^{-4} - 10^{-5}$ which is at the limit of the available experimental arrays. In the past years several attempts to measure the $\gamma$-feeding of SD configurations have been

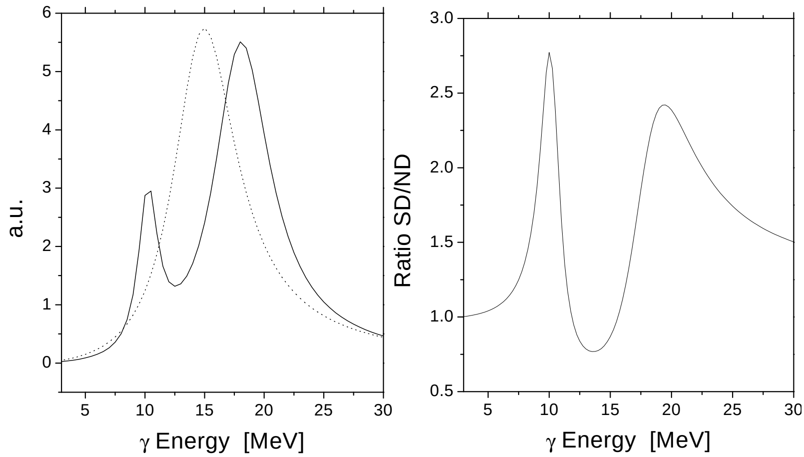


Fig. 1. In the left panel the GDR strength function in the spherical ($E_0$=15 MeV) and in the superdeformed case (where 33% of the EWSR are in a Lorentzian centered at 10.5 MeV and $\Gamma$=3 MeV while the remaining 66% is centered at 17 MeV with a width of 6.5 MeV). In the right panel the ratio between the two left curves normalized to 1 at 3 MeV is displayed.

done and published [9–13] but such a demanding high sensitivity has made the results non conclusive and in some case contradictory.

A good candidate for such kind of study is the nucleus $^{143}$Eu. In fact: *(i)* $^{143}$Eu has a rather high particle binding energy ($E_{\rm B} \simeq 10.8$ MeV) so that there is enough phase space for a high energy GDR gamma ray to be emitted, *(ii)* $^{143}$Eu presents, at high spin, both a strong discrete superdeformed band (1% of the total) and an intense E2 quasi-continuum of excited superdeformed bands [14], *(iii)* at low spin a quasi-spherical (ND) and triaxially deformed (TD) shapes [15–18] coexist and both the SD yrast band and the superdeformed quasi-continuum follow decay routes which end up to spherical low spin states (ND) only.

Therefore one should see the $\gamma$ decay of the GDR build on superdeformed states by comparing the high energy $\gamma$-ray spectra gated by discrete superdeformed transitions and by low spin triaxial transitions.

In an experiment [13] previously performed by coupling the Nordball (which consisted of 17 HPGe detectors and a multiplicity filter) with the HECTOR array (for the detection of high energy $\gamma$-rays) an indirect evidence of the GDR built on superdeformed states in $^{143}$Eu has been obtained by comparing the high energy spectrum in coincidence with ND discrete transitions with that in coincidence with the TD ones. In that experiment an excess of gamma rays centered around 10 MeV was observed and interpreted as the low energy component of the superdeformed GDR.

In this paper we discuss the results of a new experiment on $^{143}$Eu searching for evidence of a GDR built on superdeformed states. The measurement has been made using the EUROBALL spectrometer coupled with the HECTOR array. The experimental apparatus is several times more powerful than that used in Ref. [13] so that it has been possible to gate directly on discrete superdeformed transitions.

## 2. The experiment

The experiment was performed at the Legnaro National Laboratory of INFN in Italy using EUROBALL (which consists of 15 Cluster and 26 Clover HPGe detectors) coupled with 8 Large $BaF_2$ crystals from the HECTOR array placed at 30 cm from the target. Four small $BaF_2$ crystals placed at $\simeq$ 5 cm from the target provided the time reference for time of flight measurements used to discriminate neutrons. High energy gamma-rays (3–30 MeV) detected in the $BaF_2$ crystals have been measured in coincidence with low energy discrete transitions detected in Cluster and Clover HPGe detectors.

The absolute experimental full energy peak efficiency for high energy $\gamma$-rays in the $BaF_2$ detectors was approximately 1%, while for low energy transitions in EUROBALL was approximately 8%. Because of the high spin of the reaction the efficiency of the 4 small $BaF_2$ was effectively 100%.

The used reaction was $^{110}$Pd($^{37}$Cl, $4n$)$^{143}$Eu at a beam energy of 165 MeV. The $^{110}$Pd target was 97.3% pure and 950 $\mu$g/cm$^2$ thick with an Au backing of 15 mg/cm$^2$. The chosen bombarding energy represents a good compromise for a good population of the superdeformed band and for E1 emission of the final residual nucleus around the yrast line. 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 the Swiatecki model [19] and 68 $\hbar$ by the model of Winther, [20].

Approximately $4.5 \times 10^8$ events of coincidence between low energy discrete $\gamma$-transitions (measured by EUROBALL array) and high energy ($E_\gamma > 3$ MeV) $\gamma$-ray (measured in the large $BaF_2$) have been accumulated. The average multiplicity of EUROBALL data was 3 and up to 8–9 fold events have been registered. The time resolution for neutron discrimination in time of flight measurements was $\simeq$ 1 ns for $BaF_2$ and 8 ns for HPGe. The gain of each $BaF_2$ detector was monitored continuously by a LED source and small shifts have been corrected by an off-line analysis.

## 3. Experimental results

As previously discussed, it has been experimentally measured [14, 17, 18] that both the superdeformed yrast band and the excited superdeformed states of the E2 continuum follow decay routes leading to ground state that do not populate the triaxial (TD) configuration but only spherical (ND) configuration. In fact, the barrier between the SD and the triaxial energy potential minima is larger than the barrier between the superdeformed and spherical minima [15]. Consequently, the triaxially gated spectrum contains all those cascades which never pass through SD configurations.

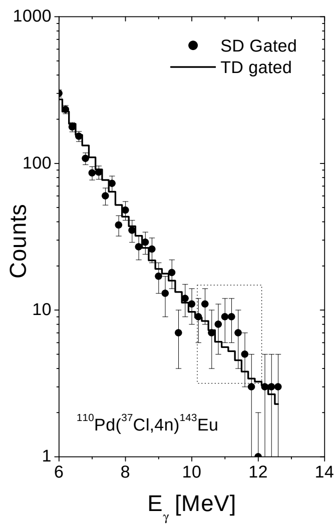


Fig. 2. Comparison of the high-energy $\gamma$-ray spectrum double gated by the lines of the superdeformed yrast band (filled circles) with the spectrum gated by lines of the triaxial configuration.

In figure 2 we show and compare two high-energy $\gamma$-ray spectra. One is gated by two SD transitions of the yrast line and the other by the transitions from the first excited states and by any transitions of TD type. The SD gated spectrum, normalized at 5 MeV, shows a clear excess between 10–12 MeV relative to the TD gated one, exactly where one expects the low energy component of the GDR. As the statistics dies at 13 MeV nothing can be said for the second high-energy GDR component which is expected to lie at 17 MeV.

Even thougt all the gammas of figure 2 come from the decay of the GDR and are gated by $^{143}$Eu discrete SD transitions, not all the $\gamma$ in the spectrum come from a GDR built on $^{143}$Eu in a superdeformed configuration. In fact, GDR $\gamma$ emission is present from the very first to the last steps of the decay of the compound and consequently some of the gamma might be emitted by low deformed hot $^{147-144}$Eu before particle emission leads to the $^{143}$Eu residue. However, as the particle binding energy of $^{143}$Eu is 10.8 MeV, approximately 70 % of the 7–12 MeV $\gamma$-rays in coincidence with $^{143}$Eu residue are emitted by $^{143}$Eu at an excitation between 8–15 MeV, exactly where a SD Giant Dipole Resonance state is expected to be.

The high statistics and the good quality of the data has allowed to extract the intensity of the discrete $^{143}$Eu SD band as a function of the energy of the $\gamma$-rays measured in coincidence. The transitions of the SD band have been identified by producing several $\gamma$-$\gamma$ matrix gated by different interval of the high energy $\gamma$-rays measured in the $BaF_2$. The Doppler correction for the superdeformed band has been applied on an event by event basis [21]. The SD band is clearly visible in coincidence with $\gamma$-rays up to 6–8 MeV (see figure 3).

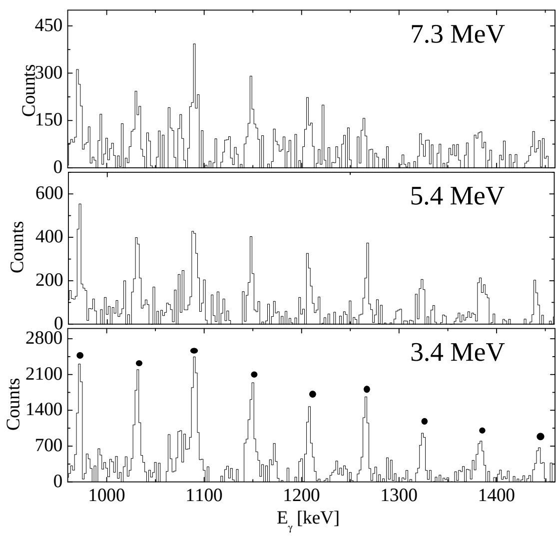


Fig. 3. The superdeformed yrast transitions (shown by the dots in the lower plot) measured in HPGe detectors in coincidence with different windows of high energy $\gamma$-rays measured in the $BaF_2$ detectors. In the right upper part of each plot the average energy of the coincident $\gamma$-rays is shown.

In figure 4, the intensity population of the discrete superdeformed band (filled squares) has been plotted relative to the energy of the coincident high energy $\gamma$-rays. The 917 keV transition from the first excited state over the $11/2^-$ isomeric state of $^{143}$Eu has been used as a reference. In the same plot the relative increase of the intensity of the E2 superdeformed continuum and of the SD ridges with high energy $\gamma$-ray is also shown with filled points

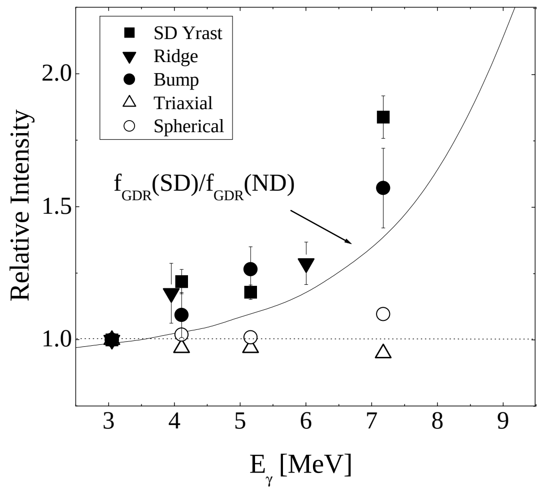


Fig. 4. Intensity of the SD yrast band (filled squares), SD ridges (filled triangles) and of SD E2 continuum (filled points) as a function of the energy of the gating transitions, normalized at 3 MeV. The empty points and triangles indicate the intensity of low lying triaxial and spherical transitions. 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 E1-decay from the GDR.

and triangles respectively. In all three cases an enhancement of a factor of $\simeq 1.5$–2 is present indicating that the E1 cooling enhances the population of all the superdeformed configurations as suggested by Ref. [6, 7]. The measured enhancement is compared with that expected as due to the different strength GDR functions in the normal case and in the superdeformed one. The continuous line is the same shown in the left panel of figure 1.

The larger measured values could reflect both level density effects as well as the fact that the high-energy gating transitions do not all end necessarily on the superdeformed yrast states.

## 4. Conclusions

The recent experimental data here discussed show evidence of a GDR built on superdeformed states and that a stable superdeformed configuration exist only few MeV over the yrast line in the high spin region. Such results confirm the indications of Ref. [13].

The experimental fact that the intensity of the superdeformed structures (discrete and damped) increases by a factor of $\approx 2$ when one gates with high energy $\gamma$-rays clearly shows that superdeformed configurations are preferably populated by E1 cooling, namely by the decay of the superdeformed GDR.

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