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GDR IN SUPERDEFORMED NUCLEI* **

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A search for the γ decay of the Giant Dipole Resonance built on superdeformed nuclear configurations was made. The superdeformed states of the ^{143}Eu nucleus were populated using the reaction ^{110}Pd(^{37}Cl,4n)^{143}Eu at a beam energy of 165 MeV. High energy γ-rays were detected in 8 large BaF$_2$ scintillators in coincidence with discrete transitions measured with part of the NORDBALL array (17 HPGe detectors and a 2π multiplicity filter). Spectra of high-energy γ-rays gated by low-energy transitions from states fed by the superdeformed bands show an excess yield in the 7-10 MeV region with respect to those gated by transitions from states not populated by the superdeformed bands. Because the dipole oscillation along the superdeformed axis of the nucleus is expected to have a frequency corresponding to $\approx$ 8 MeV (low energy component of the GDR strength function), the present result gives the first experimental indication of γ-ray emission of the GDR built on a superdeformed states.

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1. Introduction

A very vital area of research is the γ-spectroscopy of excited nuclei formed making use of heavy-ion fusion reaction. Measurements of discrete low energy transitions and continuous spectra up to energies of the order of 25 MeV have allowed to investigate different interesting aspects of the nuclear structure of excited rotating nuclei. Among these there are the study of superdeformation and that of the giant dipole resonance based on compound states. The first aims at the understanding of nuclear structure under the influence of the very strong distortion of nucleonic orbitals induced, in fast spinning nuclei, by the centrifugal and coriolis forces. The second aims at the understanding of the structure of highly-excited rapidly rotating nuclei and of the damping mechanisms of collective states at finite temperature.

Several studies of the GDR in compound nuclei at excitation energy $E^* = 30$–100 MeV were made by measuring the strength function and the angular distribution of high energy dipole photons. Changes in nuclear deformation of the hot compound nuclei due to temperature and to angular momentum were found and interpreted with the model of thermal fluctuations.

The problem of superdeformation has also been extensively studied for many nuclei in different mass regions by measuring discrete transitions among rotational superdeformed bands. In spite of the progress made concerning this topic, it is not presently known how a nucleus in a superdeformed configuration is produced out of the fused system. The nucleus could be superdeformed already directly from the beginning or it could develop this shape later in time as a component of the compound system. Because of the coupling to the nuclear quadrupole deformation, the strength function of the GDR built on a superdeformed nucleus is expected to have a component at low energy (at around 7 to 9 MeV) corresponding to the vibration on the long nuclear symmetry axis. It has been suggested [1] that the rather intense population of superdeformed bands (of the order of 1%) is related to this large splitting of the giant dipole resonance based on the superdeformed minimum. This implies that the E1 cooling of the nucleus leading to superdeformed bands should be enhanced as compared to the standard cooling rates.

It is very difficult to address experimentally the question of the population of the superdeformed bands. In fact, even finding out whether the GDR is present in a superdeformed nucleus implies measurements of the γ-decay of the GDR in coincidence with discrete transitions of the superdeformed bands, namely a sensitivity of the order of 10^{-5}, so far not yet possible.

In the following we discuss the first experiment aiming at searching a signal of the γ-decay of the GDR in the superdeformed ^{143}Eu. As discussed in the next sections this nucleus has two peculiar features that can be exploited for this search: *(i)* it has an intense superdeformed continuous at high spins ($I > 40\ \hbar$), *(ii)* at low spins is has two configurations (one normally and the other triaxial deformed) and the decay from the superdeformed configuration populates only one of these configurations (the normally deformed). As a consequence, it was possible to address the problem of the superdeformed GDR measuring high-energy γ-rays gated by intense low spin transitions. Indications for a Giant Dipole Oscillation along the long axis of the prolate superdeformed nucleus were found.

2. The ^{143}Eu case

The nucleus ^{143}Eu is a good case for searching the GDR in superdeformed shapes because the population of the superdeformed excited states was found to be particularly strong. In fact, a collective quasicontinuum of transitions forming a pronounced bump in the energy region 1250–1750 keV, has been observed at high spins and was shown to originate from superdeformed states [2]. This rotational continuum collects $\approx$ 50% of the total intensity flow at spin $\approx 50\ \hbar$.

The nucleus ^{143}Eu is characterized by a very complex and irregular level scheme at low spins, due to the coexistence of both spherical (ND) and triaxially deformed (TD) shapes [3, 4], while a strong superdeformed minimum (SD) dominates at high angular momenta. The population of the superdeformed excited states is particularly strong since the crossing between ND and SD yrast lines occurs at rather low angular momenta as compared with other nuclei ($I \approx 40\ \hbar$). This leaves $\approx$ 20 units of angular momentum available for a favourable population of the SD states in the quasicontinuum, between the fission cutoff at high spins and the enhanced mixing with normal states in the $I = 40\ \hbar$ region.

Both the superdeformed yrast band and the superdeformed excited states follow decay routes leading to g.s. that populate low spin states of the spherical shape only. The intense quasicontinuum bump was found to be very pronounced in coincidence with ND transitions and to disappear in coincidence with TD transitions.

It is therefore expected that if the GDR exists on a superdeformed state one should see it by comparing high energy spectra gated by low spin transitions of the spherical shape (populated by the superdeformed transitions) with those gated by low spin transitions of the triaxial shape (not populated by the superdeformed transitions). This is the basic idea behind this work, that does not make use of high-energy γ-rays gated by discrete transitions of superdeformed lines, whose measurement is beyond the limit of standard detector array and would require the use of large array such as EUROBALL or GAMMASPHERE. In addition, the particle binding energy in ^{143}Eu is quite high ($\simeq$ 11.2 MeV) and consequently the emission of γ-rays with energy in the interval 7–10 MeV (energy at which the low energy component of the GDR is expected to be) competes favourable with that of neutrons.

3. The experiment

The experiment was performed at the Tandem accelerator laboratory of the Niels Bohr Institute in Risø (Denmark). The ^{37}Cl beam, at the incident energy of 165 MeV, impinged on a two stacked targets of ^{110}Pd (97.3% pure and 510 and 550 μg/cm^2 thick). 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 [5] and 68 $\hbar$ by the model of Winther, in which the excitation of collective modes is taken into account in the formation process [6]. Measurements with lower statistics were also made at E_{beam} = 160 and 170 MeV to study the GDR in the difference spectrum as a function of spin.

The experimental apparatus used was a particular configuration of the NORDBALL detector array and consisted of 17 HPGe detectors, a multiplicity filter (inner ball) covering a solid angle of $\approx 2\pi$ (made with 30 small BaF_2 detectors) and 8 large volume BaF_2 detectors of the HECTOR array for the high energy γ-rays. The detection efficiency for high energy gamma rays was $\approx$ 1%, approximately the same of that for low energy γ-rays. The total efficiency of the multiplicity filter was around 35%. The gain of each big BaF_2 detectors has been monitored continuously (every 3-5 minutes) during all the experiment using a LED source and small shifts were corrected during the off-line analysis. Because of too large gain fluctuations (larger than 5%) the data relative to two of the BaF_2 detectors were rejected. The calibration of the HPGe detector was obtained using sources of ^{152}Eu and ^{60}Co while the big BaF_2 were calibrated using the 15.1 MeV gamma produced by the reaction $^{11}B + D = ^{12}C^* + n$.

We have accumulated events containing coincidences among a high energy gamma rays ($E\gamma > 3$ MeV) measured in the BaF_2 detectors and γ-rays detected in HPGe and the multiplicity filter (for ten days of beam time). During the experiment only HPGe folds equal or larger than 2 where recorded, but because of the lack of statistics, the data were subsequently unfolded.

Table I shows the population of residual nuclei for the neutron channels (measured in coincidence with high energy gamma rays) corresponding to three spin windows. The dependence of the low-energy γ-ray spectrum

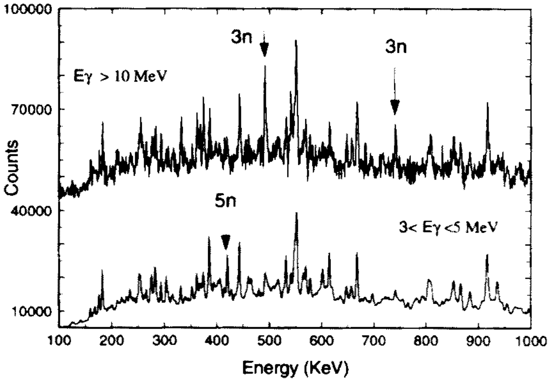

Fig. 1. The HPGe spectrum measured in coincidence with 3 MeV $< E_\gamma <$ 5 MeV (lower spectrum) and with $E_\gamma >$ 10 MeV (upper) are displayed. The arrows show some of the clean transitions in ^{142}Eu and ^{144}Eu. It is interesting to notice how the gate on high-energy γ-rays enhances the population of the ^{144}Eu channel.

on the energy of the gating high-energy γ-rays was investigated and some results are shown in Fig. 1. In this figure two HPGe spectra are shown, one associated with 3 MeV $< E_\gamma <$ 5 MeV and the other with $E_\gamma >$ 10 MeV. As expected, in the latter spectrum the lines of the 3n channel are enhanced because γ-rays with $E_\gamma >$ 10 MeV replace a neutron and 4n is the most intense channel when the gating with high-energy γ-rays 3 MeV $< E_\gamma <$ 5 MeV.

TABLE I

Table containing the fraction of the measured residues in coincidence with a $E_\gamma >$ 3 MeV gamma rays at different values of the angular momentum I.

Residue	Total Population	$\langle I \rangle \simeq 25\hbar$	$\langle I \rangle \simeq 45\hbar$	$\langle I \rangle \simeq 55\hbar$
^{142}Eu	13%	23%	13%	8%
^{143}Eu	73%	67%	74%	70%
^{144}Eu	14%	10%	13%	22%

The intense continuum in the region E_γ = 1250–1750 keV observed at bombarding energy of 160 MeV for ^{143}Eu, is also seen at the present bombarding energy of 165 MeV in the HPGe spectrum associated to the decay of all the residual nuclei, and it is shown in the right part of Fig. 2. Also in this case one can see the typical behaviour of the the continuum formed by damped rotational transitions, namely the bump increases and moves with increasing spin.

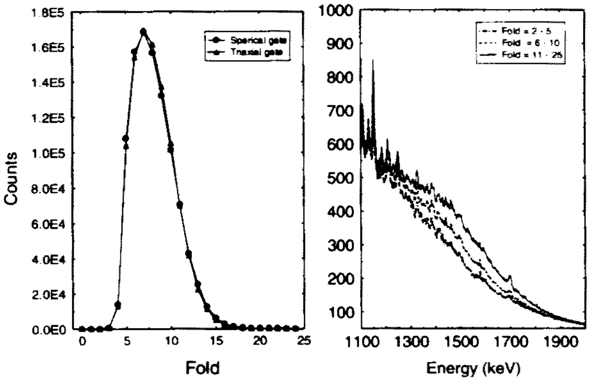

Fig. 2. Left panel: the fold distribution measured with the multiplicity filter in coincidence with the selected TD transitions and with the selected ND transitions. Right panel: The HPGe spectra in the energy window between 1.1 MeV and 2.0 MeV measured in three fold windows. The displayed events are singles, namely without any gate on discrete ^{143}Eu transitions.

The fold distributions measured with the Innerball associated to the two different decay paths that are used in the following discussion are shown in the left part of Fig. 2. One can see from this figure that the fold distribution in coincidence with ND transitions is very similar to the one in coincidence with TD transitions. The spectra discussed in the following sections were obtained gating on the coincidence fold of the multiplicity filter that was divided in 3 intervals: 2–5 (low fold gate), 6–10 (medium fold gate), and 11–25 (high fold gate)

4. Results

As described in Section 2, the idea followed to search for evidence of the GDR in superdeformation is based on the study of ratios of high energy γ-rays gated by different intense transitions measured with the HPGe. We define three classes of gates: *(i)* one consisting of ND low spin transitions that are known to be populated by the superdeformed configuration, *(ii)* one consisting of low spin TD transitions that are known not to be populated by the superdeformed configuration, *(iii)* the intense superdeformed continuum at E_γ = 1200–1800 keV formed by all residual nuclei, but in large fraction ($\approx$ 60–70%) made of damped superdeformed transitions of ^{143}Eu.

The gates of the three types are shown in Fig. 3 in the top, middle and bottom part, respectively. The high energy spectra gated by spherical and triaxial transitions and associated to the medium fold interval, which has the best statistics, are compared in Fig. 4. We note already in the

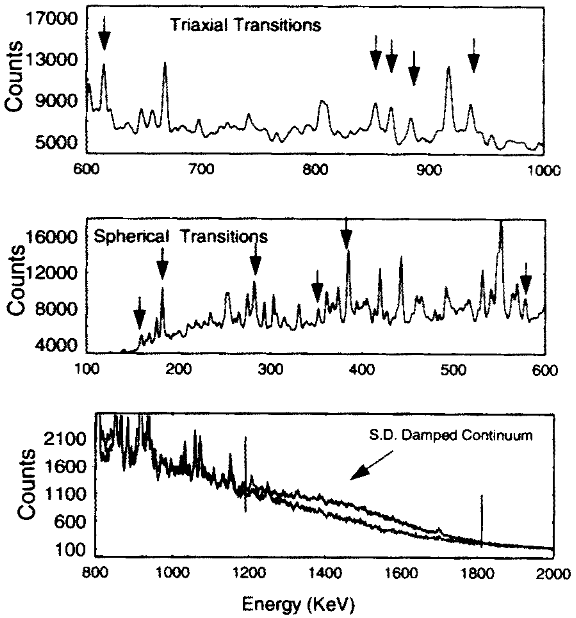

Fig. 3. Lines associated to the TD configuration are indicated in the top panel, those of the ND configuration in the middle panel and the part of the continuous spectra used to gate high-energy γ-rays is shown in the bottom.

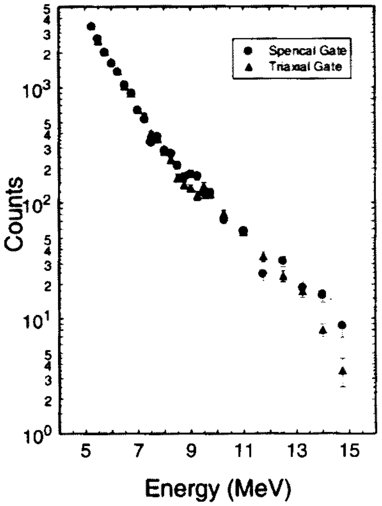

Fig. 4. The BaF$_2$ spectra gated by ND (filled point) and TD (filled triangles) transitions are shown. The data are relative to the medium fold interval ($\langle I \rangle \simeq$ 45 $\hbar$) which has the best statistics.

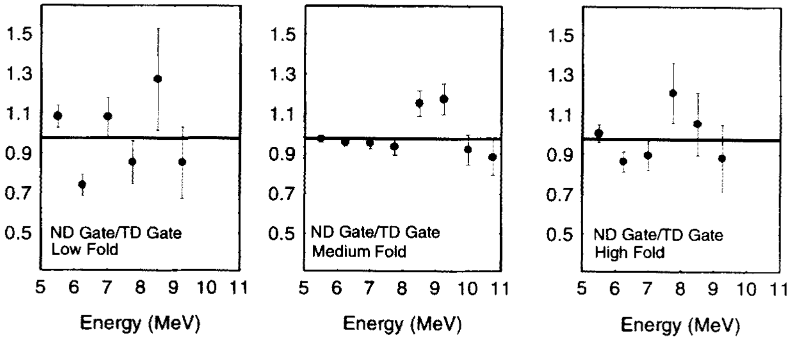

Fig. 5. The ratio of the high-energy γ-rays spectrum gated by ND-transitions to that gated by TD-transitions is shown for three spin windows, namely $\langle I \rangle \simeq 25\,\hbar$ (left panel), $\langle I \rangle \simeq 45\,\hbar$ (middle panel), $\langle I \rangle \simeq 55\,\hbar$ (right panel). The data have been binned to 750 keV due to the low statistics. It is important to remember that the TD gate tags a decay which do not pass through a superdeformed configuration while the ND gate tags a decay containing contributions from the decay of the superdeformed nucleus.

logaritmic plot that the spectral shape is different in the region 7 MeV $< E_\gamma <$ 10 MeV. This difference should not be due to the fact that choosing these two different classes of transitions we choose different spin region of the compound because the two types of transitions have very similar fold distributions (cf. Fig. 2).

The ratio of these two spectra is shown in the middle panel of Fig. 5. In the figure the same ratio is shown for the two other fold coincidence intervals associated to lower and higher spins. One can notice that only in the case of the medium fold interval there is a clear excess of γ-ray yield in the region of the low energy component of the GDR in the superdeformed nucleus. It is not clear at the moment if the less pronounced effects at higher spins could be related to some phase space cut off effects for the gamma emission as compare to that of neutron occurring at γ transition energy of the order of the neutron binding energy or if it is connected to the lack of statistics. On the other hand, the first possibility is supported by the fact that the difference between high-energy spectra measured at $E_{\mathrm{beam}} = 160$ and 170 MeV was found at high spins larger than at low spins. That finding, which in [7] was interpreted as a an indication for superdeformation, also shows that one might find a stronger signal for the superdeformation using a bombarding energy larger than that of the present work.

Because the present evidence for the low-energy component of the GDR in the superdeformed nucleus is based on ratio of spectra, it is very important to check whether our reference spectrum, namely the one that does not contain the feeding from superdeformation, is a really good reference. In order to do this we have compared high energy spectra gated by two sets of transition belonging to triaxial shapes and two sets to the spherical shape. This comparison is shown in Fig. 6, where different combinations of spectra are displayed. Two points are worth noticing in connection to this figure. One, and the most important, is that the two spectra gated by the two different sets of triaxial transitions are basically the same. The second is that it seems that some of the spherical transitions are not fed exactly in the same way by the superdeformed configurations.

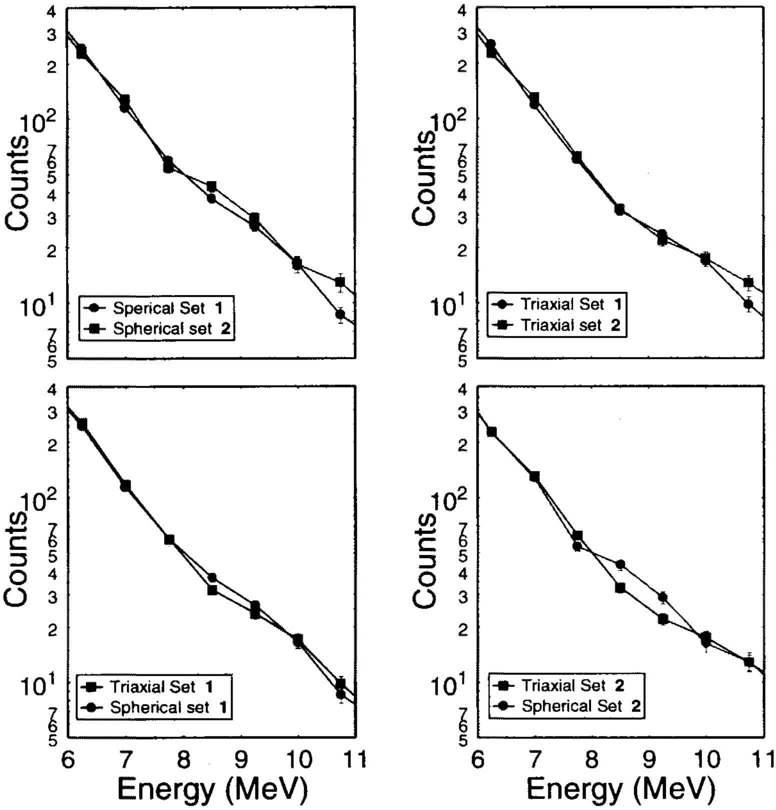

Fig. 6. BaF_2 spectra measured in coincidence with the two triaxial and the two spherical subsets of lines. In the top part we compare two high-energy γ-rays spectra in coincidence with the spherical subsets (left plot) and with the triaxial (right plot). In the bottom part we compare of the TD- and ND-gated BaF_2 spectra.

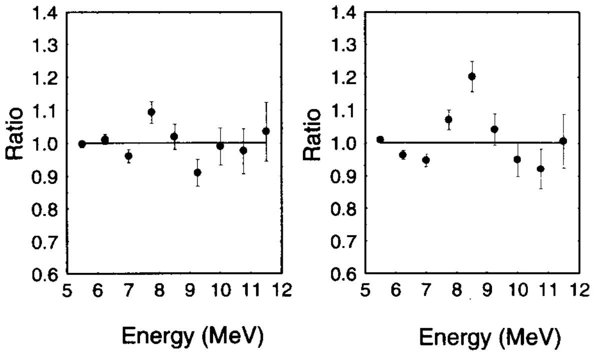

Fig. 7. The ratio of the BaF_2 spectrum gated by the continuous bump to the ND-gated spectrum is shown in the left panel, while the ratio of the BaF_2 spectrum gated by the continuous bump to the TD-gated spectrum is shown in the right panel.

The last ratio of high energy spectra to be discussed is that obtained gating with the continuum bump relative to triaxial and to spherical transitions. This is shown in Fig. 7. One can see that the ratio between spectra gated by the continuous bump relative to triaxial transition has again some enhancement in the region 7–10 MeV as compared to the one relative to spherical transitions. Note that the excess is smaller than that of Fig. 5 or Fig. 8, and this could be due to the fact that transitions in the continuum used as a gate are not all of ^{143}Eu. The results of Fig. 7 seems to be consistent with the conclusion reported in Ref. [2], namely that the continuous bump is made mainly of superdeformed transitions.

5. Conclusion

In this paper we have presented the results of an experiment aiming at finding evidence for the GDR resonance on a superdeformed nucleus. In the case of the chosen nucleus, ^{143}Eu, we have studied ratios of high energy spectra gated by low energy γ transitions belonging to three different classes: *(i)* TD transition, not fed by SD nucleus, *(ii)* ND transition, partially fed by SD nucleus, *(iii)* SD continuous bump. The main conclusion obtained from the present work is summarized in Fig. 8. The high energy γ-ray spectra gated by the ND transitions (left part of Fig. 8) and that gated by the SD bump (right part of Fig. 8) both relative to that gated by TD transitions show some excess in the region where the low component of the GDR built on a superdeformed nucleus is expected to be. In addition, the fact that the ratio among the bump-gated and the TD-gated spectra gives

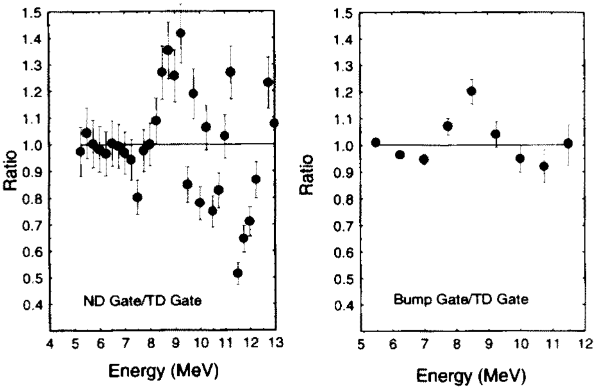

Fig. 8. Figure summarizing the results: In the left panel the ratio between the high-energy γ-rays spectrum gated by ND transitions and by TD transitions binned to 250 keV. The data are relative to the $\langle I \rangle \simeq 45\ \hbar$ case. In the rigth panel the ratio between BaF_2 spectrum measured in coincidence with the superdeformed dumped continuum and the one in coincidence with TD transitions is shown.

results similar to the ratio among the ND-gated and the TD-gated spectra supports previous conclusions that the bump at E_γ = 1250–1750 keV is made out of superdeformed transitions [2].

However, the present finding needs to be confirmed with further measurements. In particular, it would be important to have measurements at different excitation energies (one at E_{beam} = 175 MeV is presently being analysed) and to have measurements of high energy γ-rays gated by superdeformed discrete transitions. The latter should be within the reach of the new generation of gamma detector array (EUROBALL, GAMMASPHERE) that have enhanced sensitivity to such rare events. Studies of this type should be carried out, to learn more about nuclear structure of hot rotating nuclei and in particular on collective modes and on how exotic nuclear configuration are excited.

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