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Nuclear Physics A687 (2001) 237c–244c

NUCLEAR PHYSICS A

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The Giant Dipole Resonance in superdeformed nuclei and the feeding of superdeformed bands

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The low energy component of the Giant Dipole Resonance built on the superdeformed ^{143}Eu has been observed by measuring high-energy γ-rays in coincidence with selected discrete transitions. The EUROBALL array coupled to the HECTOR' large volume BaF_2 detectors was used. The data show that a stable superdeformed configuration survives only in a very limited part of the phase space which is confined at very high spin (I >40) and covers excitation energies at only few MeV above the yrast line.

1. Introduction

Exclusive measurements of the γ-decay of the Giant Dipole Resonance (GDR) in compound nuclei have produced substantial progresses in the study of the properties of hot rotating nuclei and of the damping mechanisms of collective states at finite temperature.

The GDR intrinsic width ($\Gamma^{\downarrow}$) has been found to remain substantially constant [1] with spin and temperature. The angular momentum dependence of the GDR width has been explained in terms of deformation effects induced by the centrifugal forces, which are particularly strong in medium-light nuclei [2]. The measured increase of the width with temperature [3] has been associated to thermal fluctuations related to the large ensemble of shapes characterizing hot nuclei [4].

In the case of the decay of excited compound nuclei, the measured high-energy γ-ray spectra contain contributions from all the different decay steps at various energies starting from that of the initial formation down to the ground state of residual nuclei. For photon energies larger than the particle binding energies E_B, the γ-decay yield increases with excitation energy while exactly the opposite happens for photon energies smaller that E_B. Consequently, GDR photons in normally deformed nuclei, having an energy much larger than E_B, sample the nuclear properties close to that of the initial formation of the compound and are completely decoupled to any final configuration of the residual nuclei. The E1 decay at energy around the particle binding energy are instead expected to provide information on the final cooling process of compound nuclei leading to the feeding of particular nuclear configurations. A very interesting case is the population of the superdeformed configuration via E1 decay.

In spite of the extensive work made concerning the superdeformation problem, it is

PII S0375-9474(01)00627-3

not presently known how a superdeformed (SD) nucleus is produced out of a compound nucleus. Since the time of the discovery of the first superdeformed band [5,6], 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 [7,8]. The E1 transition probability at $E_\gamma \approx$ 9-11 MeV for the GDR decay built on superdeformed configurations is expected to be much larger than that of normal deformed states due to both the line 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 (that corresponding to the dipole oscillation along the nuclear symmetry axis of a superdeformed collective prolate nucleus) is shifted from $\approx$ 15 MeV to $\approx$ 10 MeV, an energy close to the neutron binding energy favoring, consequently, the γ-decay of the GDR into a superdeformed state.

Therefore, in the case of the giant dipole resonance built on highly rotating nuclei with energy around the yrast line one expects a definite correlation (due to the very different strength functions) between the measured high-energy γ-rays and the low-energy γ-rays emitted by the residual nuclei in different nuclear configurations. Experimentally it is very difficult to address this problem, particularly in connection with superdeformed configurations. In fact, one has to isolate and measure the cascades containing a high energy γ-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 require an experimental sensitivity of the order of 10^{-4}-10^{-5} which is at the limit of the available experimental arrays.

Several attempts to measure the γ-feeding of SD configurations have been done and published [9–12] in the last ten years but such a demanding high sensitivity has made the results non conclusive and in some case contradictory.

In an experiment [13] previously performed with the array NORDBALL (which consisted of 17 HpGe detectors and a multiplicity filter) coupled to the HECTOR array (for the detection of high energy γ-rays) some evidence of the GDR built on superdeformed states in ^{143}Eu has been obtained, although in an indirect way, by comparing the high energy spectrum in coincidence with ND discrete transitions (fed by superdeformed configurations) with the one in coincidence with TD transitions(which are NOT populated by superdeformed configurations). 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. However, the statistics was rather poor pointing to the necessity for a new and better experiment.

In this paper we report the first direct experimental observation of the low energy component of the GDR built on a superdeformed configuration of ^{143}Eu. The used reaction is the same used in reference [13]. The paper is organized in 5 sections. In section 2 the experimental details of the HECTOR-EUROBALL apparatus are described while in the following sections the data relative to the ^{37}Cl + ^{110}Pd = ^{147}Eu* reaction starting from a more inclusive analysis (section 3) and ending up to the more exclusive GDR spectra (section 4) are discussed. Conclusions and perspective are given in the last section.

2. The experiment

The experiment was performed at the Legnaro National INFN laboratories in Italy using EUROBALL (which consisted in that case of 15 Cluster and 26 Clover HpGe detectors for a total of 206 Compton suppressed HpGe channels) coupled to the HECTOR high-energy detectors (8 large BaF_2 crystals). Four additional small BaF_2 detectors from the HECTOR multiplicity filter were inserted in the set up to obtain a good time reference for the time of flight measurement used for γ-neutron discrimination.

High energy γ-rays (5-30 MeV) detected in the BaF_2 crystals were measured (with an estimated absolute full energy peak efficiency of $\approx$ 1% at 15 MeV) in coincidence with low-energy discrete transitions detected in Cluster and Clover HpGe detectors (measured with an absolute efficiency of $\approx$ 8% at 1 MeV).

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. The calibration of HpGe detectors has been performed using ^{60}Co and ^{152}Eu sources while the BaF_2 detectors have been calibrated using the 15.1 MeV gamma-rays produced in the reaction ^{11}B (19.1 MeV) + D = $^{12}C^{*}$ +n .

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 the 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 Swiatecki model [14] and 68 $\hbar$ by the model of Winther, [15].

We have accumulated events containing coincidences among high energy γ-rays measured in BaF_2 crystals ($E_\gamma > 3$ MeV) and γ-rays measured in HpGe detectors which have triggered at least three HpGe crystals. Additionally at least one of the four small BaF_2 detectors should have fired.

3. The GDR in the hot Eu compound

Before discussing the HECTOR-EUROBALL data we present the results of an experiment performed using the same ^{37}Cl + ^{110}Pd reaction at three different bombarding energies (160, 165 and 170 MeV) and at two coincidence fold windows (corresponding to two different angular momentum windows).

In this experiment high-energy γ-rays have been measured with the HECTOR array coupled to NORDBALL (an array of 17 HpGe detectors) and a multiplicity filter covering 2π of the solid angle. A complete discussion on the experimental setup and on the data-analysis can be found on reference [16].

The measured spectra of high-energy γ-rays of the hot rotating ^{147}Eu nucleus and of its daughter nuclei have been analyzed and reproduced with statistical model calculations together with the yield distribution of the final residues . The left part of figure 1 shows the spin dependence of the extracted GDR width (obtained using one Lorentzian strength function for the GDR) in comparison with theoretical predictions based on the thermal fluctuation model (continuous-line for T=1.2 MeV and dashed-line for T=1.4 MeV) [17]. A calculation based on the more phenomenological formula of ref [18] is also shown (dotted

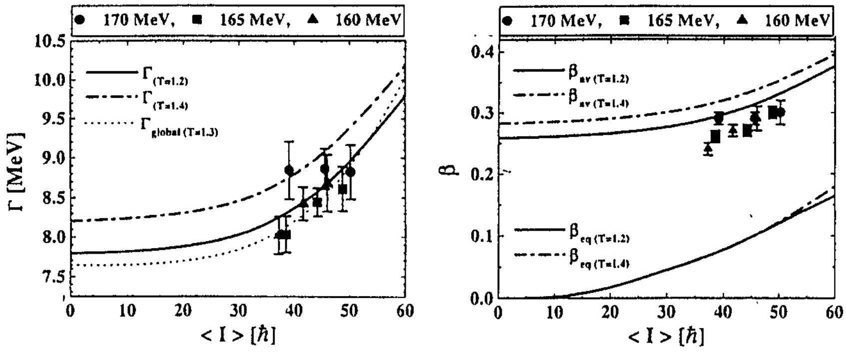

Figure 1. The measured GDR width obtained from a single Lorentzian fit (left panel) and the deformation parameter β deduced from a two Lorentzian analysis are plotted relative to the angular momentum [16]. The calculation within the thermal fluctuation model [17] are shown with a continuous line for T=1.2 MeV and with a dashed line for T=1.4 MeV. The dotted line shows the prediction of the parameterizations of ref [18].

line). In the right part of figure 1 the size of the quadrupole deformation extracted from the experiment using a GDR strength function of two Lorentzian type is displayed as a function of the angular momentum. In the same plot the calculated average and most probable nuclear deformations are also shown.

The results of these rather inclusive data do not show the presence of the decay from superdeformed configurations and therefore a much better cascade selection is needed to observe a GDR in a superdeformed nucleus.

4. GDR in the superdeformed ^{143}Eu nucleus

The nucleus ^{143}Eu has a superdeformed yrast band populated with an intensity of the order of 1% and a strong quasi-continuum of superdeformed nature for spin larger than 45 $\hbar$ with an intensity of the order of 40% [19].

At low spin this nucleus has a quasi-spherical (ND) and a triaxially deformed (TD) shapes [20–23]. Both the SD yrast band and the superdeformed quasi-continuum follow decay routes which end up to populate spherical low spin states (ND) only. Therefore one should see the γ-decay of the GDR built on superdeformed states by comparing the high energy γ-ray spectra gated by either discrete superdeformed transitions (SD) (if possible) or by low spin ND transitions and by low spin triaxial (TD) transitions (the latter tagging the cascades which DO NOT pass through superdeformed configurations).

These quasi-unique features of ^{143}Eu make such nucleus an excellent case for the search of the decay from a superdeformed GDR.

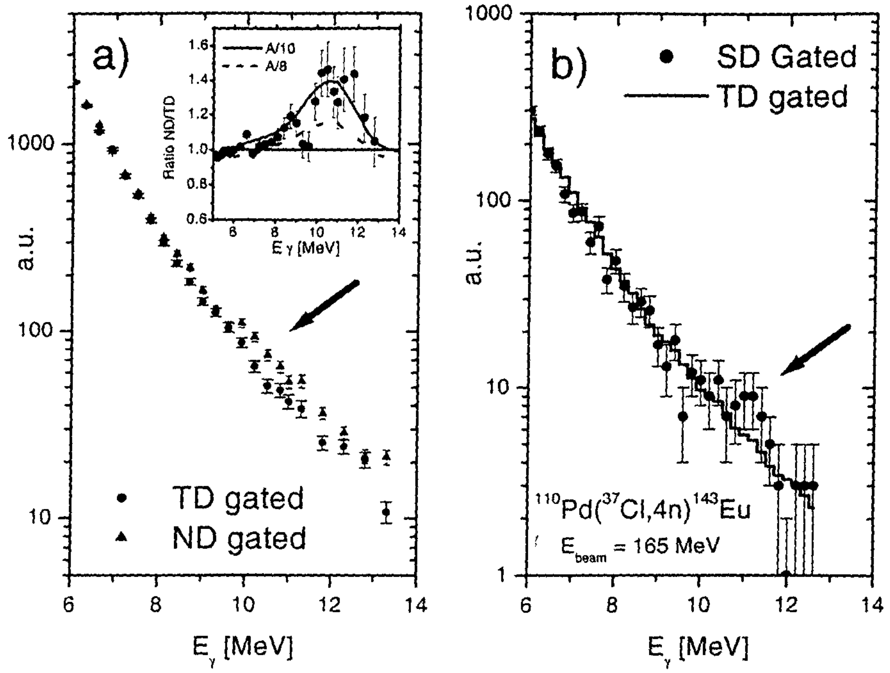

Figure 2. *Left panel:* The spectrum shown with filled triangles is double gated by two spherical transitions (populated by the SD decay); the other (filled circles) is double gated by the low-energy transitions of the triaxial configuration. In the inset the ratio spectrum obtained by dividing the two 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.

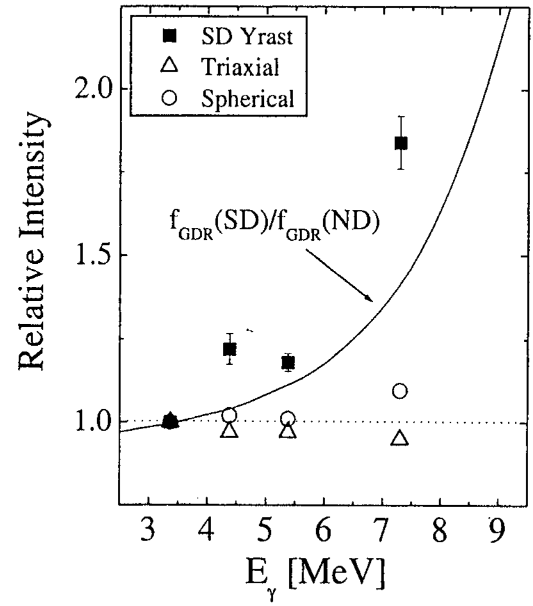

Figure 3. Intensity of the SD Yrast band (squares), of low lying triaxial (triangles) and spherical (circles) transitions as a function of the energy of the gating high-energy transition, normalized at 3 MeV. The full drawn line represents the ratio between the superdeformed GDR strength function and the spherical one, giving the lower limit for the feeding of a SD nucleus by E1-decay from the GDR.

As reported in ref [13] the high-energy γ-ray spectra in coincidence with ND and TD discrete transitions were extracted. In the present analysis the additional condition of coincidence with the first excited states of ^{143}Eu was applied to select better the 4n channel. The left part of figure 2 shows, with filled triangles, the measured high energy γ-ray spectrum in coincidence with ND transitions (fed by superdeformed configurations) and with filled points the one in coincidence with TD transitions (which are NOT fed by superdeformed configurations). A definite excess of γ-rays is evident in the ratio of the two spectra (displayed in the inset), at energies between 9-12 MeV, where the low energy component of the superdeformed GDR is expected to be.

The shape, position and intensity of the presently measured excess are not only in agreement with the previous data with poorer statistics [13] but also confirm that the superdeformation survives only few MeV above the yrast line as deduced from the statistical model calculations shown in the inset of figure 2 (left panel). The experimental ratio was reproduced assuming that at 40-55 $\hbar$ and up to 15 MeV above the yrast 40% of the cascades which end in the ND part pass through a superdeformed configuration [19]. The dashed line corresponds to the level density parameter a=A/8 in the SD region while the continuous line corresponds to a=A/10.

A more direct evidence of the GDR on SD nuclei can be found in the spectrum gated by the yrast transitions of the SD band. In fact, the high statistics and the good quality of the HECTOR-EUROBALL data has allowed to extract for the first time the high-energy γ-ray spectrum in coincidence with two transitions of the SD yrast band. This spectrum is shown in the left panel of figure 2 and is compared with the high-energy spectrum (continuous line) gated by TD transitions. Again an excess of gamma-rays is clearly visible at 10-11 MeV.

It is important to stress at this point that, since the high-energy gamma-rays emitted in the very first steps of the cooling processes should not have any correlation with the different configurations of the residues, the measured excess yield should be due to the emission at the very last stages of the cooling process (leading to the feeding of SD configurations). This conclusion can be checked by studying the relative intensity of the discrete SD Yrast band gated by high-energy γ-rays at different values of the energy of the gating transitions. In figure 3 the filled squares give the relative intensity of the superdeformed band normalized to 1 at $E_\gamma = 3$ MeV while the empty circles and triangles give the relative intensity of transitions between states of spherical and of triaxial shapes, obtained with the same procedure used for the SD yrast transitions. The population intensity of the transitions was determined using as a reference the low lying transition at 917 keV.

Figure 3 clearly shows that the intensity of the yrast superdeformed band is almost doubled when measured in coincidence with high-energy γ-rays in contrast with that of the triaxial and spherical transitions showing a quasi-constant behaviour. The solid line of figure 3 shows the ratio between the strength function of the superdeformed GDR (E_{1GDR} = 10.5 MeV, Γ_{1GDR} = 3 MeV with 33 % of EWSR strength and E_{2GDR} = 17 MeV, Γ_{2GDR} = 6.5 MeV with 67 % of EWSR) with the spherical GDR (E_{GDR} = 14.5 MeV Γ_{GDR} = 5 MeV, 100% of EWSR), normalized to the data at 3 MeV. Such curve gives the most simple estimate for the case in which the GDR is directly feeding the superdeformed band. The larger measured values could very likely reflect level density effects.

5. Conclusion

In this paper the results of a recent experiment made with EUROBALL in a special set-up including the HECTOR detectors for high energy γ-rays have been presented. From these data three relevant conclusions have been obtained: i) the data show for the first time a direct evidence of the low energy component of the GDR built on the warm ^{143}Eu nucleus in a SD configuration; ii) the intensity of the spectrum in the region of the low energy component of the GDR evidences that the superdeformed configurations (characterizing this nucleus at high spins) survive only few MeV above the yrast; iii) the relative intensity of the discrete superdeformed yrast band was found to be almost two times larger when high-energy gamma-rays are measured in coincidence. This last point shows that the E1 cooling is a preferred way to populate cold/warm superdeformed configurations.

Also the analysis of the more inclusive data confirms that the superdeformation is a property of a very small region of the phase space which can be identified with extremely exclusive measurements that can be made only with the large arrays presently available.

The present results call for future studies in other mass regions and for microscopic calculations of the giant dipole resonance in superdeformed nuclei at very high spins to obtain a more general and deep understanding of this interesting problem.

6. Acknowledgements

This work is based on an experiment performed by a large collaboration with the EUROBALL array. In particular, we thank the participation of N. Blasi and Benzoni from University of Milano and INFN sez of Milano , J. Styczen and M. Zieblinski from the Niewodnizanski Institute of Nuclear Physics - Krakow, M. Bergstrom, B. Herskind, from the Niels Bohr, A. Algora, A. Gadea, R.Isocrate from Laboratori Nazionali di Legnaro, J. Nyberg and A. Axelsson from the Department of Radiation Sciences, Uppsala University, G. Lo Bianco from the University of Camerino, M. Castoldi and A. Zucchiatti from INFN sez. of Genova. The work has been supported by the Italian Istituto Nazionale di Fisica Nucleare, by the Danish and Swedish Natural Science Research Council and by the Polish Committee for Scientific Research (KBN grant No.2 P03 B001 16).

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