Observation of a double giant dipole resonance in fusion-evaporation reactions

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The emission of two coincident energetic ($E \geqslant 8$ MeV) gamma rays has been observed in the 187 MeV $^{37}Cl+{}^{120}Sn$ reaction by using the cluster detectors of the EUROBALL III array. Those events are attributed to the decay of the double giant dipole resonance built on highly excited states.

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I. INTRODUCTION

The recent observation of the double giant dipole resonance (DGDR) in heavy-ion and pion-induced reactions has attracted considerable interest [1]. The observed resonance energy and width are in good agreement with the representation of the DGDR as a multiphonon state formed by noninteracting harmonic oscillators. The main interest in the study of the properties of these multiphonon states is in the search for phonon-phonon interaction and anharmonic effects.

In this respect, an interesting field of investigation is represented by the possible dependence of the anharmonicity on the nuclear temperature and its correlation with the observed DGDR parameters. Detailed theoretical predictions show, indeed, a positive correlation between temperature, strength, and width of the resonance [2]. The available experimental data about DGDR are related to resonances built on the ground state of nuclei, excited by inelastic collisions, electromagnetic excitation, or pion-induced double charge-exchange reactions. Therefore, a direct test of the theoretical predictions is not possible at this stage. A natural way to study temperature effects on the DGDR would be the use of heavy-ion-induced fusion-evaporation reactions, once the possibility to discriminate the DGDR contribution from the bulk of the compound nucleus decay will be demonstrated.

From the experimental point of view, fusion-evaporation reactions have been intensively employed in the past to study GDR in hot nuclear systems, mainly with the detection of energetic γ rays emitted in the decay of the resonance [3]. As demonstrated in an earlier experiment performed with the two-arm photon spectrometer detector system, the DGDR can be tagged by detecting the two coincident energetic photons emitted in the decay of the two one-phonon states [4].

In this respect, some high efficiency γ-ray spectrometers, even if mainly designed for nuclear spectroscopy, can also be used to measure energetic photons. This is the case of the EUROBALL III array, in which a number of germanium cluster detectors [5] are employed, covering about 4% of the total solid angle.

We report in this paper on the search for DGDR events in the decay of highly excited compound nuclei. To this end, a large data set from an experiment performed during the Legnaro campaign of EUROBALL III has been reanalyzed. This experiment was originally performed to search for hyperdeformed states in the reaction 187 MeV $^{37}Cl+{}^{120}Sn$ that populates the compound nucleus ^{157}Ho at an average excitation energy of $E_x = 83$ MeV. Results from this experiment have been already published [6].

II. DATA ANALYSIS

The data set considered here contains about 6×10^9 EUROBALL events with a trigger condition of having at least five (unsuppressed) γ rays in coincidence with charged particles detected in the Italian Silicon Sphere array [7] or at least seven γ rays (unsuppressed) without the coincidence with charged particles. The single elements of cluster and clover detectors participated in the trigger definition as individual detectors. We note that this trigger requirement is supposed to enhance fusion-evaporation events rejecting lower gamma-ray multiplicities as those associated with two-body reactions.

In the present analysis, the 15-cluster detectors have been calibrated by using a combination of low energy radioactive sources and the 6.1-MeV γ ray produced in the inelastic scattering of the evaporated neutrons on the oxygen nuclei contained in the bismuth germanate scintillator of the anti-Compton shields. After the calibration, each cluster was considered as a single detector, performing the add-back of the seven Ge detectors and the anti-Compton suppression. Symmetric γ-γ matrices have been then built considering only coincidences between cluster detectors. The inclusive γ-γ matrix contained 4×10^9 events. Furthermore, matrices were

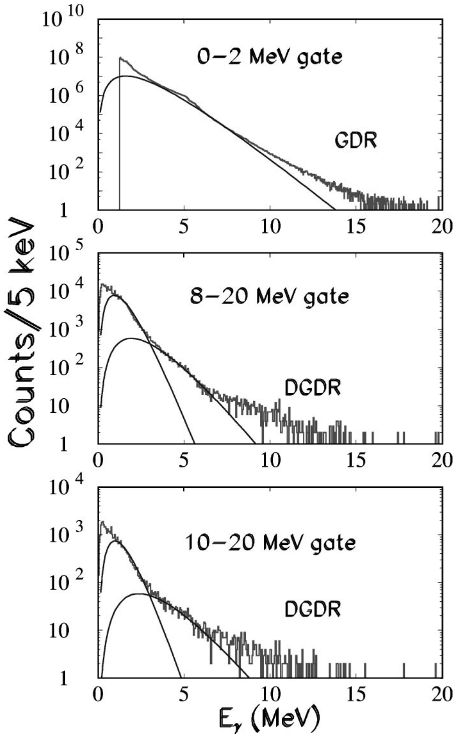

FIG. 1. Gamma-ray spectra obtained by setting gates on one axis of the inclusive (symmetric) gamma-gamma matrix. Only coincidences between cluster detectors have been considered. Lines are results from fits to the experimental data. For details see the text.

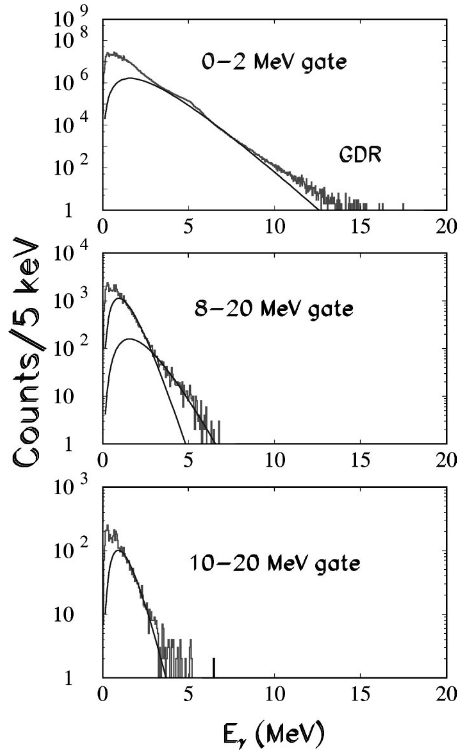

FIG. 2. Same as Fig. 1 but for events in coincidence with protons.

also built considering exclusive events in coincidence with protons or alpha particles. Those matrices contained about 1×10^9 events each.

It has to be stressed that the time resolution of the Ge detectors and the short-flight path do not allow the suppression of the neutron-induced events in the gamma-ray spectrum. In any case this effect is minimized by the fact that the cluster detectors are located at backward angles where the neutron flux is lower.

III. EXPERIMENTAL RESULTS

A. Two-energetic-photon events

Gamma-ray spectra, obtained by setting gates (0–2 MeV, 8–20 MeV, and 10–20 MeV) on one axis of the inclusive and exclusive (i.e., in coincidence with protons or alpha particles) matrices, are reported in Figs. 1–3, respectively.

The slope of each spectrum has been fitted with the well-known function

$$F(E_\gamma)=N_0 E_\gamma^{2L+1}\exp(-E_\gamma/T_{eff})$$

in order to derive the shape of the gamma-ray continuum that defines the background for the giant resonance Lorentzian distribution. In this formula N_0 is a normalization constant, L is the multipolarity of the gamma-ray transitions, and T_{eff} is the effective temperature of the nuclear states populated by photon emission. Since it is expected that the higher energies in the gamma-ray spectrum are dominated by transitions with dipole character, a $L=1$ value has been used. Furthermore, we have considered in the fit only the part of the spectrum between 5 and 8 MeV, where a dominant contribution from statistical transitions is expected [8].

For the $E_{\gamma,1}=0-2$ MeV gate, deviations from the fitted function are observed in Figs. 1–3 both for gamma-ray energies lower than $E_{\gamma,2}\sim 5$ MeV and larger than $E_{\gamma,2}\sim 8$ MeV. At lower energies this is due to the well-known bump of quadrupole transitions ($E_{\gamma,2}<3$ MeV) and to structures at $E_{\gamma,2}\sim 5-6$ MeV resulting from the interaction of the evaporated neutrons in the detector itself. At the higher energies ($E_{\gamma,2}>8$ MeV), the extra yield with respect to the extrapolated-continuum distribution is attributed to contributions from GDR decay.

As far as the fit of the continuum is concerned, we note that the effective temperature extracted from the inclusive spectrum obtained with the 0–2 MeV gate, $T_{eff}=0.5$ MeV, is very close to that determined by fitting the gamma-ray spectrum predicted by standard statistical model calculations performed with the CASCADE code [9], folded with the cluster response function simulated with the GEANT code [10].

Furthermore, we note that the the GDR contribution is less evident in the spectra obtained in coincidence with protons or alpha particles. In fact, as confirmed by statistical model calculations, the charged-particle emission takes place in this reaction mainly in the first step of the deexcitation cascade, reducing the high energy photon emission probability from lower excitation energies. This is particularly evident by comparing the inclusive and the alpha-particle gated spectra. The slightly lower effective temperature, T_{eff}

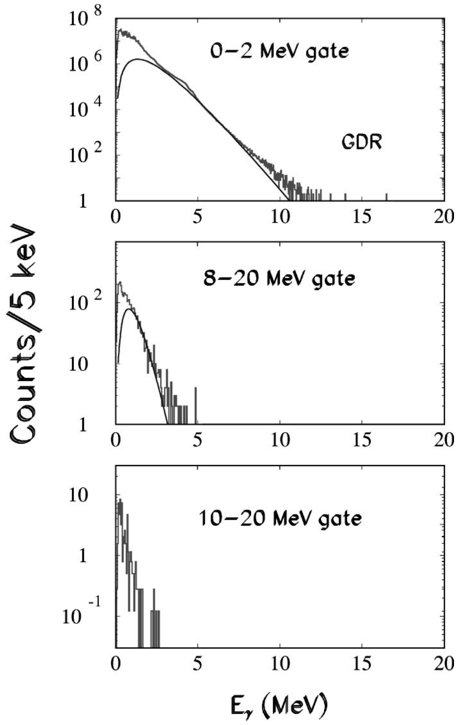

FIG. 3. Same as Fig. 1 but for events in coincidence with alpha particles.

$=0.45$ MeV, extracted from the spectrum in coincidence with alpha particles demonstrates indeed the reduction of the average excitation energy available for the gamma emission after the particle decay.

As shown in Figs. 1–3, the cuts $E_{\gamma,1}=8$–20 and $E_{\gamma,1}=10$–20 MeV select events in which one energetic photon, including those from the GDR decay, has been already emitted. These gated spectra show different features for inclusive and exclusive events.

In the case of the inclusive gamma-ray spectrum, three different components are clearly identified. A low energy component ($E_{\gamma,2}\leqslant 3$ MeV) represents the bulk of the statistics and is interpreted as due to gamma-ray transitions emitted along or in the vicinity of the yrast line. This means that the most probable two-photon event occurs when the energetic gamma ray is in coincidence with a statistical transition at the bottom of the deexcitation cascade, where the gamma decay competes more effectively with the particle emission. This component is characterized by a very low effective temperature ($T_{eff}\sim 0.3$ MeV), as expected. In addition, a second component is present, characterized by a higher value of the effective temperature, $T_{eff}=0.7$–0.8 MeV. This component is supposed to be due to the statistical emission from higher excitation energies in the compound nucleus decay. Finally, an extra yield with respect to the statistical continuum is seen at energies $E_{\gamma,2}>8$ MeV. In the latter events two energetic photons are emitted in the same deexcitation chain. These events are strongly suppressed in the *p*- and alpha-gated spectra shown in Figs. 2 and 3, demonstrating again that after the charged-particle decay the remaining excitation energy is too low to allow the emission of two energetic gamma rays.

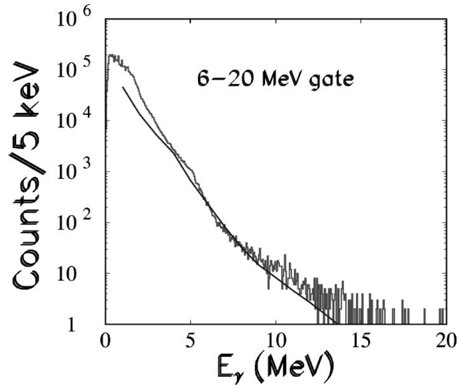

FIG. 4. Comparison between the experimental spectrum (gate 6–20 MeV on the inclusive matrix) and predictions from statistical model folded with the calculated cluster response function (line). For details see the text.

Whether or not the two-energetic-photon events ($E_{\gamma,1}>8$ MeV, $E_{\gamma,2}>8$ MeV), clearly seen in the inclusive spectra, are originating from two GDR decay or are simply due to coincidences between one statistical transition and one GDR photon will be discussed in the next section.

To further investigate the origin of the events characterized by the coincidence of two energetic gamma rays, a spectrum was obtained by gating the inclusive matrix on the window $E_{\gamma,1}=6$–20 MeV. This gate was selected to obtain good statistics with a large suppression of events coming from reaction different from fusion evaporation. The resulting spectrum, shown in Fig. 4, is compared with the predictions from statistical model calculations. In the calculation the decay from the nominal excitation energy is considered and a single GDR resonance (energy $E=15$ MeV, strength $S=1$, and width $\Gamma=8$ MeV) is taken into account. The predicted spectrum has been then folded with the cluster response function. It appears that the shape of the predicted spectrum reproduces the gross features of the experimental one, with a slight overestimation of the effective temperature in the statistical region. This discrepancy between calculation and experiment is due to the fact that the predicted spectrum contains only single, hard gamma-ray events whereas the experimental one contains double energetic gamma-ray events in which one of the two is certainly being emitted from higher excitation energy, thus decreasing the average effective temperature. We stress the fact that the comparison between calculated and experimental spectra has not been pushed further due to the uncertainties in the cluster response function and the impossibility to reject neutron-induced events with the present setup.

B. DGDR events characterization

The probability of the one- and two-energetic-photon events has been estimated assuming that the total statistics in the inclusive matrix represent the global number of fusion reaction events and applying efficiency correction for the cluster detectors.

In this hypotheses, we found that the multiplicity of energetic photon ($E_\gamma\geqslant 8$ MeV) emission is, considering the inclusive events:

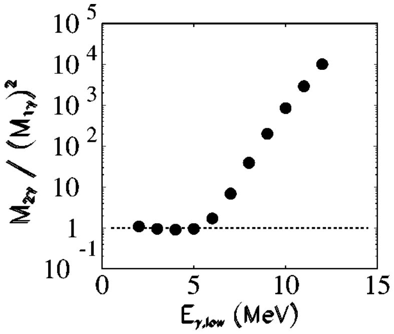

FIG. 5. Ratio between the multiplicity for two-photon events $M_{2\gamma}$ and that corresponding to the uncorrelated emission of two gamma rays $(M_{1\gamma})^2$ as a function of the lower limit of the gate window $E_{\gamma,low}$. The statistical error of the ratio is within the symbol size.

$$M_{1\gamma}\sim 5\times 10^{-4}$$

whereas that associated with the emission of two energetic photons ($E_{\gamma,1}\geqslant 8$ MeV, $E_{\gamma,2}\geqslant 8$ MeV) is

$$M_{2\gamma}\sim 1\times 10^{-6}.$$

We note that the latter multiplicity is much larger than that characteristic of the emission of two uncorrelated energetic photons in the same compound nucleus decay. An upper limit for this probability can be roughly estimated neglecting the decrease of the hard gamma-ray yield due to the lowering of the excitation energy after the first gamma-ray emission. In this hypotheses we obtain

$$M_{2\gamma,incor}\sim (M_{1\gamma})^2\sim 2\times 10^{-7}.$$

This simple comparison seems to demonstrate that the bulk of the two-energetic-gamma-ray events is associated with the DGDR decay. However, the gate $E_\gamma\geqslant 8$ MeV is quite close to the energy region affected by the neutron-induced events, that are not rejected in the present experimental setup. To rule out effects due to such contamination, the ratio $M_{2\gamma}/(M_{1\gamma})^2$ has been determined as a function of the lower limit of the gate window $E_{\gamma,low}$. Results are reported in Fig. 5. It appears that for $E_{\gamma,low}\leqslant 5$ MeV, the value of the ratio is close to unity. In fact, under those conditions, the two-photon events are dominated by coincidences between uncorrelated statistical γ rays. By increasing $E_{\gamma,low}$, the weight of photons from the giant dipole resonance decay increases with respect to the background due to statistical transitions. Data points in Fig. 5 for $E_{\gamma,low}\geqslant 8$ MeV exhibit a very large value of the ratio, demonstrating the dominance of the two photons correlated events. This result rules out the possibility that large ratios are caused by contaminations from neutron-induced events, not expected at the higher $E_{\gamma,low}$.

As a final test, we have studied the correlation between the two emitted gamma rays in the same way used in Ref. [4] to study DGDR in cold systems. To this end, the γ-γ matrices have been transformed into sum versus difference two-dimensional arrays, i.e., $E_{\gamma,1}+E_{\gamma,2}$ versus $E_{\gamma,1}-E_{\gamma,2}$.

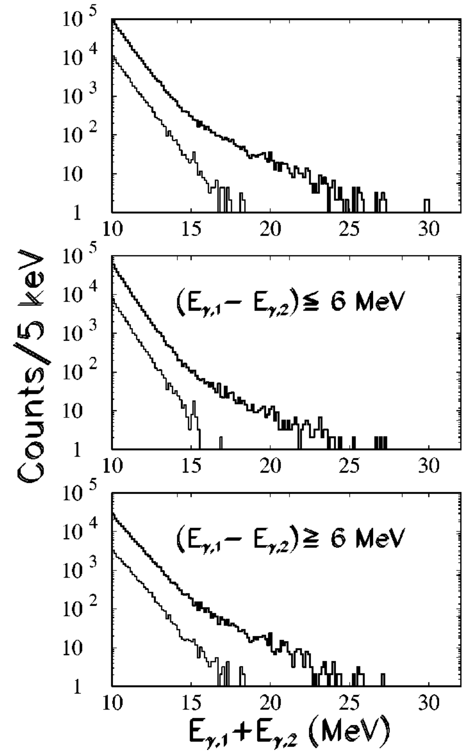

FIG. 6. Sum energy spectra $(E_{\gamma,1}+E_{\gamma,2})$ obtained without (upper panel) and with (medium and lower panels) conditions on the difference between the coincident gamma rays $(E_{\gamma,1}-E_{\gamma,2})$. In each panel the upper (thick line) histogram refers to inclusive events, the lower (thin line) to coincidences with protons.

Following Ref. [4], sum-energy spectra $(E_{\gamma,1}+E_{\gamma,2})$ were obtained for any value of the energy difference between gamma rays as well as for specific conditions on the energy difference. In particular, it is required that the two photons have roughly the same energy, i.e., $(E_{\gamma,1}-E_{\gamma,2})\leqslant 6$ MeV, or, alternatively, a large energy difference, i.e., $(E_{\gamma,1}-E_{\gamma,2})\geqslant 6$ MeV. The resulting distributions are reported in Fig. 6 for inclusive and exclusive (proton coincidences) events. In the inclusive case, the sum spectrum $(E_{\gamma,1}+E_{\gamma,2})$ exhibits a change of shape characteristic of the dipole resonance in highly excited systems, due to the folding of the characteristic resonance Lorentzian distribution with the exponential falloff of the level density. The centroid of this contribution is located roughly at $E_\gamma\sim 20$ MeV, the double of the one in the spectra of Fig. 1. This observation supports strongly the DGDR nature of such events. Moreover, events around 20 MeV are strongly suppressed in the exclusive spectrum that, in this case, seems to exhibit only the exponential tail due to the statistical continuum. This suggests that DGDR events became experimentally undetectable in the evaporation from nuclei of mass $A\sim 160$ at excitation energies of about 70 MeV, corresponding to the average excitation energy in daughter nuclei after the proton decay.

Furthermore, the condition on the difference between the two gamma rays, used in Ref. [4] for selecting the DGDR events in cold nuclei in the case $(E_{\gamma,1}-E_{\gamma,2})\leqslant 6$ MeV, seems not to be effective in case of highly excited nuclei.

The spectra reported in Fig. 5 show, indeed, the same gross behavior for all conditions. This is certainly due to the different strength distribution of dipole resonances in hot nuclei with respect to cold systems. In highly excited systems, indeed, the width of the resonance is intrinsically larger and its strength is distributed over a wide energy interval due to the effect of the exponential tail of the level density.

IV. SUMMARY AND CONCLUSIONS

We have studied in this work the correlations between gamma rays emitted in the reaction 187 MeV ^{37}Cl+ ^{120}Sn, populating the compound nucleus ^{157}Ho at an average excitation energy of $E_x=83$ MeV. This study was focused on events in which two energetic ($E_\gamma \geqslant 8$ MeV) photons are emitted, searching for the decay of the DGDR built on highly excited states.

We have found that the shape of the gamma-ray spectrum obtained by requiring the coincidence with a second photon having energy in the range $E_\gamma=6-20$ MeV is roughly accounted for by statistical model predictions. This demonstrates that such two-photon events are produced essentially in the fusion-evaporation reaction.

The shape of the inclusive spectrum of gamma rays in coincidence with photons in the range 8–20 MeV is characterized by regions showing two different effective temperatures. The events associated with a low effective temperature are supposed to be emitted at the end of the particle evaporation phase. The events characterized by a very high effective temperature that are thought to be emitted at the top of the deexcitation cascade. Those events are strongly suppressed when a coincidence with charged particles is required.

The events in which two photons in the GDR region ($E_\gamma>8$ MeV) are emitted are characterized by a multiplicity value that is larger than the estimated upper limit for the emission of two uncorrelated photons in the same deexcitation cascade. This evidence supports strongly the attribution of such events to the decay of the double giant resonance built on highly excited states. Moreover, the sum spectrum of the two photon events shows the well known line-shape of a giant dipole resonance in hot systems, with the centroid energy twice the one for a single GDR.

In conclusion, we have presented evidence for DGDR events in fusion-evaporation reaction. This opens the possibility to study temperature effect on two-phonon states. Any further investigations would require the use of high efficiency gamma-ray detection systems with better response function at high gamma energy and the suppression of neutron-induced events. This might allow future line-shape studies of the resonance thus determining DGDR parameters as a function of the excitation energy. On the other hand, an upgrade of the available statistical model codes, taking into account DGDR excitation and decay, is also required to analyze the experimental gamma-ray spectra.

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