MAPPING THE GDR QUENCHING IN NUCLEI OF MASS $A = 120$–132^*

D. Santonocito[a], Y. Blumenfeld[b], C. Maiolino[a], R. Alba[a]
G. Bellia[a,c], R. Coniglione[a], A. Del Zoppo[a], E. Migneco[a,c]
P. Piattelli[a], P. Sapienza[a], L. Auditore[d,e], G. Cardella[d]
E. De Filippo[d], E. La Guidara[d], C. Monrozeau[b], M. Papa[d]
S. Pirrone[d], F. Rizzo[a,c], A. Trifiró[d,e], M. Trimarchi[d,e]
H.X. Huang[f], O. Wieland[g]

[a]Laboratori Nazionali del Sud — INFN, via S. Sofia 62, 95123 Catania, Italy
[b]Institut de Physique Nucléaire, CNRS-IN_2P_3, Université Paris-Sud
Université Paris-Saclay, 91406 Orsay Cedex, France
[c]Dipartimento di Fisica e Astronomia dell'Universitá di Catania
via S. Sofia 64, 95123 Catania Italy
[d]INFN — Sezione di Catania, via S. Sofia 64, 95123 Catania Italy
[e]INFN — Dipartimento di Scienze MIFT dell'Universitá di Messina
v.le F. Stagno d'Alcontres 31, 98166 S. Agata, Messina, Italy
[f]Key Laboratory of Science and Technology for National Defense
China Institute of Atomic Energy, P.O. Box 275(46), Beijing 102413, China
[g]INFN — Sezione di Milano, via Celoria 16, 20133 Milano Italy

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A comprehensive study of the evolution of the GDR properties from $E^* = 150$ MeV to $E^* = 430$ MeV has been undertaken in nuclei of mass $A = 120 \div 132$. The experimental investigation was performed using MEDEA detector. An onset of a quenching of the GDR gamma yield was found at $E^* = 270$ MeV comparing the experimental gamma-ray spectrum with statistical model calculation. The quenching effect increases at $E^* = 330$ MeV and is even more pronounced when the analysis is extended to higher excitation energies using data from previously performed experiments. The comparison with phenomenological models describing the quenching phenomenon gives a qualitative explanation for the effect but is not able to reproduce its detailed features as a function of excitation energy. A smooth cut-off approach describes reasonably well the progressive disappearance of the dipole strength, which occurs around 220–230 MeV excitation energy, and shows that the GDR quenching is a rather sharp effect.

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1. Introduction

The study of Isovector Giant Dipole Resonance (GDR) in nuclei allows one to probe the behavior of nuclei at high temperature, providing unique information on the bulk properties of the nucleus and on the evolution of collective motion in extreme conditions up to its disappearance [1]. While the main decay mode of the GDR is through light particle emission, its gamma-decay branch is sufficiently fast to compete with other decay modes with a sizeable branching ratio and, therefore, to study the characteristics of the nuclear system prevailing at that time.

Studies of the evolution of the GDR properties with excitation energy and spin [2] were mainly focused on the mass region $A \sim 110 \div 130$ where a rather broad systematics was built. It shows that, in this region, up to about $E* = 200$ MeV, the GDR centroid energy slightly varies between 14 and 15 MeV according to the $A^{-1/3}$ dependence [3] for $T = 0$ nuclei, the strength exhausts 100% of the Energy Weighted Sum Rule (EWSR), while the width increases due to temperature, spin effects and compound nucleus lifetime from 5 MeV up to about 14 MeV [4, 5]. Above $E^* = 300$ MeV, evidences of a suppression of the GDR gamma emission were collected by different experiments [6–8]. This result could not be explained in the framework of the standard statistical model typically used to reproduce the gamma spectra and to extract the main GDR features. In fact, at higher excitation energies, the gamma multiplicity is expected to increase due to the higher number of steps available for the GDR gamma rays to compete with particle emission. In order to reproduce the data, a sharp suppression of the gamma-ray emission above a certain excitation energy, the so-called sharp cut-off was introduced, suggesting the existence of a maximum excitation energy of approximately $E^*/A \sim 2.2$ MeV for the dipole vibration [8]. This suppression of the GDR emission has been related to the equilibration time of the collective dipole vibration, which becomes longer than the particle emission time above a certain limiting excitation energy. Different theoretical explanation were developed to reproduce the experimental behavior [9–13], but no precise understanding has been achieved, due to the fair agreement between data and model predictions, and to the limited set of data available in the excitation energy region where the decrease of GDR emission sets in. In order to be able to draw clear conclusions on GDR quenching mechanism and find the energy region where the quenching appears, a complete mapping of the evolution of the GDR properties as a function of excitation energy, from a region where the GDR retains its typical feature up to a region where the quenching is clearly evident, was needed. For this reason, a study of gamma-ray emission from hot nuclei of mass $A \sim 120$–132 with excitation energies between 150 and 330 MeV was undertaken at the Laboratori Nazionali del Sud (LNS) Catania. In the following, the procedure adopted to characterize the hot nuclei in terms of their excitation energy and mass will be first described. Then gamma-ray spectra will be shown and compared to statistical model calculations to extract the GDR main parameters. Evidences of a GDR quenching were found which call for a comparison with model prescriptions of the GDR quenching at high excitation energies which will be presented and discussed. Such a comparison will be then extended to higher excitation energy data from a previous experiment to draw a comprehensive scenario of the GDR features up to 430 MeV excitation energy.

2. Experimental method and hot nuclei characterization

The study of the evolution of the GDR properties as a function of the excitation energy of system was carried out at the LNS Catania using the MEDEA multi-detector [14] coupled to SOLE solenoid and MACISTE focal plane detector [15]. Beams of ^{116}Sn at 17 and 23 A MeV impinging on ^{12}C and ^{24}Mg targets were used to study the reactions listed in Table I. Light charged particles and gamma rays were detected in MEDEA detector, a ball made of 180 BaF_2 scintillators 20 cm thick covering the polar angles from 30° to 170° degrees and the whole azimuthal angle, in coincidence with forward emitted ($\theta < 3°$) fusion-like residues focused by the magnetic field of SOLE solenoid on the focal plane detector MACISTE placed 16 m from the target. The time of flight (ToF) of the recoils was measured using three 30×40 cm^2 low-pressure Multi-Wire Proportional Chambers.

TABLE I

Values of average excitation energy and mass A of the hot nuclei populated in the reactions.

Reactions	E_{beam}	E^* [MeV]	A
^{116}Sn+^{12}C	17 A MeV	150 ± 10	124
^{116}Sn+^{12}C	23 A MeV	190 ± 10	123
^{116}Sn+^{24}Mg	17 A MeV	270 ± 20	132
^{116}Sn+^{24}Mg	23 A MeV	330 ± 20	128

Time of flight was used to identify fusion-like events. The trigger condition was given by the coincidence between one MACISTE detector and at least one MEDEA detector. The ToF spectra of the recoils show a rather broad distribution for all the reactions investigated, with a maximum close to the center-of-mass velocity, indicating the presence of complete and close to complete fusion events [16]. A velocity window centered around the center-of-mass velocity was chosen for each reaction in order to select a well-defined excitation energy and the data analysis of the light charged particle energy spectra and gamma rays was performed accordingly.

For each reaction, the excitation energy of the system was determined combining the analysis of the ToF spectrum performed applying a massive transfer model and the corrections for pre-equilibrium emission deduced from the analysis of light charged particle energy spectra. Proton, deuteron, triton and alpha-energy spectra measured in MEDEA from 42.4° to 170° were reproduced through a fitting procedure assuming isotropic emission from two Maxwellian type sources, one associated to compound emission and the other describing the pre-equilibrium emission. Since neutrons were not detected in the experiment, the pre-equilibrium neutron multiplicity was assumed equal to the proton one [17, 18]. This approach allowed to evaluate the amount of energy and mass removed in the pre-equilibrium stage of the reaction and, therefore, to estimate both the excitation energy and mass of the hot system populated in the reaction as in Ref. [19, 20]. The values of excitation energies and masses of the hot systems populated in the different reactions are listed in Table I.

3. Gamma-ray spectra

Gamma-ray spectra measured in coincidence with fusion events for all the reactions investigated are shown in Fig. 1 (a). They were built summing the contributions of detectors in the rings centred at 83° and 97° where the Doppler shift is negligible. In order to study the GDR properties, the bremsstrahlung contribution, which mainly arise from first chance *np* collisions in the pre-equilibrium stage of the reaction, has to be subtracted from the spectra. For this reason, a fitting procedure using an exponential function having slope and intensity as free parameters was applied to the spectra for energies $E_\gamma > 35$ MeV. The results of the fitting procedure are shown in Fig. 1 (a) as solid lines. The slope values extracted range from 7.9±0.3 MeV to 9.5±0.3 for the different reactions and are in agreement with systematics for nucleon–nucleon bremsstrahlung [21]. The exponential function is then extrapolated down to low energies and subtracted from each spectrum in order to obtain the statistical gamma component displayed in Fig. 1 (a) as open symbols. The error bars include both statistical error and the errors on the subtractions of the bremsstrahlung component.

Since GDR gamma rays can be emitted at all steps during the de-excitation process, the investigation of the GDR main features calls for a comparison with statistical calculations which take into account the whole decay sequence assuming as input the average excitation energy, mass and charge of the hot system extracted from the data analysis. The statistical decay code DCASCADE [22, 23] was used to reproduce the gamma spectra assuming a Lorentzian shape for the GDR with a centroid energy of 14.3 MeV for the two reactions on ^{12}C target and 14.0 MeV for those on ^{24}Mg target,

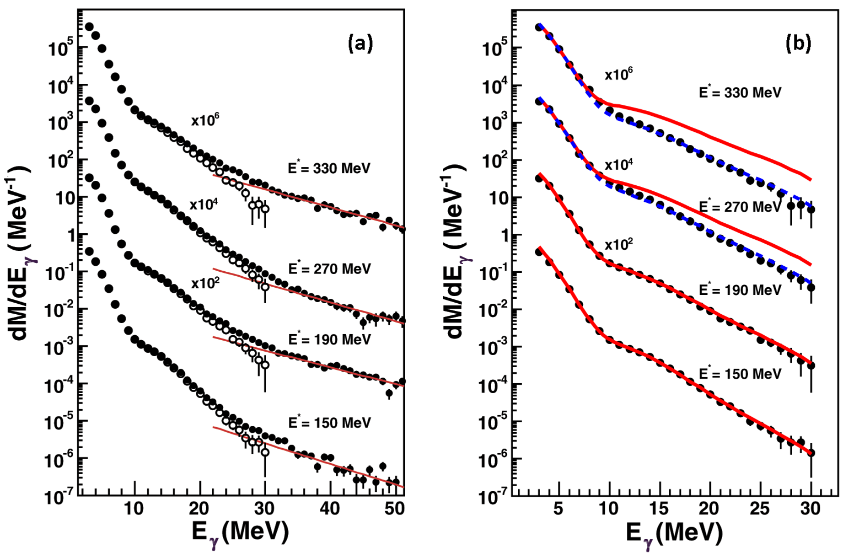

Fig. 1. (Colour on-line) (a) Gamma-ray energy spectra measured at 83° and 97° for all the reactions investigated. Solid red lines represent the fit of the bremsstrahlung component, while open symbols show the gamma spectra after bremsstrahlung subtraction. (b) Comparison of the statistical gamma spectra with DCASCADE calculations shown as solid red lines. Sharp cut-off calculations, performed at $E^* = 270$ and $E^* = 330$ MeV are indicated as dashed blue lines [25].

a width increasing with excitation energy and ranging from 11.0 ± 0.8 MeV to 13 ± 1.0, while the strength was taken equal to 100% of the Thomas–Reiche–Kuhn (TRK) sum rule. A level density parameter dependent on the temperature of the system following the Ormand parametrization [24] was adopted in the calculations. The results of the DCASCADE calculations, folded with detector response are shown in Fig. 1 (b) as solid lines and compared to the experimental spectra after bremsstrahlung subtraction. Spectra at $E^* = 150$ and 190 MeV are well-reproduced, while at $E^* = 270$ MeV, the calculation overshoots the data in the GDR region indicating the onset of a quenching effect which becomes progressively more important with increasing excitation energy as shown in the comparison at $E^* = 330$ MeV [25]. No reasonable variation of any of the input parameters can recover the observed difference in the framework of the standard statistical scenario.

In the attempt to reproduce in a simple way the data at 270 and 330 MeV, we introduced in DCASCADE a sharp suppression of the gamma yield above a fixed excitation energy. The best fit to the data was obtained assuming a cut-off energy of 230 MeV for the spectrum at $E^* = 270$ MeV and 240 MeV for the spectrum at $E^* = 330$ MeV as shown by the dashed lines in Fig. 1 (b) [25].

An overall coherent scenario emerges pointing to a sudden disappearance of the dipole vibration in hot nuclei with excitation energies around $E^*/A \sim 1.7 \div 1.8$ MeV.

4. Quenching model predictions

Theoretical approaches to explain the progressive disappearance of the GDR at high excitation energy point to two main effects to explain the data, either a rapid increase of the width or a real yield suppression. Yield suppression models proposed by Bortignon *et al.* [9] and Snover [10] predict a GDR quenching based on the interplay between the time needed for the system to equilibrate the collective degrees of freedom and the nucleus lifetime. At high excitation energies, the lifetime of the hot system reduces significantly and the system could start to cool down by particle emission before being able to develop a collective oscillation. The associated quenching factors predicted by each model were implemented in DCASCADE and the associated results, folded with detector response function, are shown in Fig. 2 (a) for the full set of reactions investigated. The comparison clearly

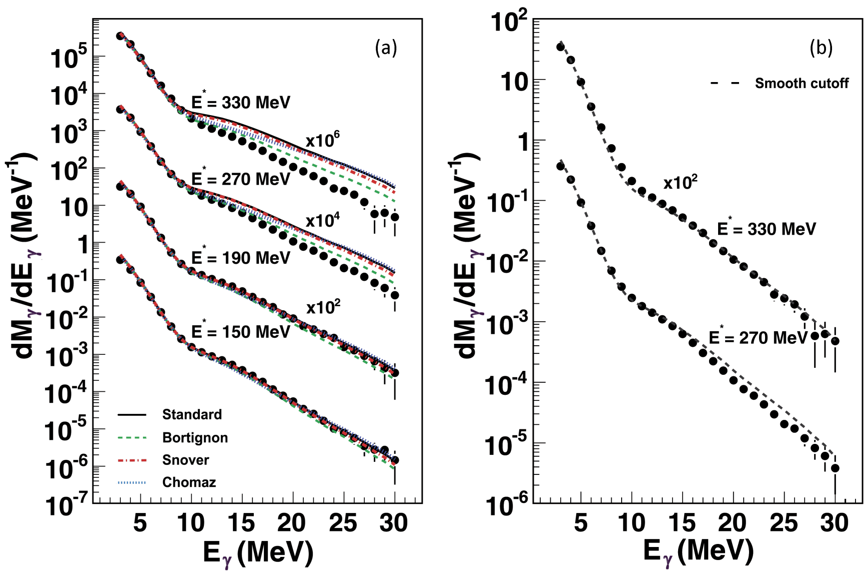

Fig. 2. (Colour on-line) (a) Gamma-ray energy spectra for the different reactions are compared to model predictions. Solid lines show standard statistical model calculations, dotted blue lines correspond to Chomaz model predictions, dot-dashed red lines to Snover predictions, while Bortignon model predictions are shown as dashed green lines [25]. (b) Comparison of the spectra at $E^* = 270$ MeV and $E^* = 330$ MeV with DCASCADE calculations assuming a smooth cut-off of the gamma emission as a function of excitation energy [25]. See the text for details.

shows that the Bortignon model predicts a progressive quenching as a function of excitation energy which arises already at $E^* = 190$ MeV, prediction not supported by the experimental data. At higher energies, the predicted quenching is not sufficient to reproduce the data which fall below the calculations. The Snover approach instead is able to reproduce data up to $E^* = 190$ MeV but predicts a rather soft quenching which is not able to describe the high excitation energy data.

A different idea based on the width increase proposed by Chomaz [13] to explain the quenching was also tested. The key issue is that each nuclear level involved in the GDR gamma decay has an intrinsic width associated to its finite lifetime due to particle evaporation. This implies that transition energies between nuclear levels cannot be determined better than twice the intrinsic width and that such indetermination should accounted for in the total GDR width. Calculations using Chomaz approach are shown in Fig. 2 (a). The comparison with the data suggests that the main effect of this approach is to remove strength from the GDR region shifting it at higher energies. This effect leads to a spectral shape which is not able to reproduce the experimental data. The comparison clearly indicates that the GDR quenching cannot be explained in terms of a width increase but is instead better explained in terms of yield suppression as in the Bortignon model. This suggests the existence of a critical temperature for the dipole vibration above which the system starts to evaporate particles before developing a collective behaviour.

Since phenomenological model prescriptions that suggest a smooth quenching as a function of excitation energy are not able to reproduce the data while the sharp cut-off appears to be an oversimplified approach, we made an attempt to reproduce the data at $E^* = 270$ and 330 MeV using a smooth cut-off function dependent on excitation energy to study the shape of the cut-off. For this reason, a Fermi function was implemented in DCASCADE and a fitting procedure was launched to find the best parameters of diffuseness and E_{cut}, the energy value at which the Fermi function reduces to one half, that reproduce the data. The best agreement was found assuming a suppression of the gamma emission above 200 MeV and using a value of 20 MeV for the diffuseness and 225 MeV for E_{cut}. The results of the calculations are shown in Fig. 2 (b) as dashed black lines. This result shows that the GDR quenching is a rather sharp effect differently from what predicted by phenomenological models.

5. GDR quenching from low to high excitation energies

In order to achieve a complete understanding of the GDR evolution up to highest excitation energies, gamma-ray energy spectra measured in the study of the reaction ^{36}Ar + ^{98}Mo at 37 A MeV performed at GANIL [16] were revisited through a comparison with new statistical model calculations. In that experiment, hot nuclei were characterized combining the information coming from the ToF of the residues with the analysis of the light charged particle energy spectra. Data were sorted into three bins in ToF corresponding to average excitation energies ranging from 300 to 430 MeV and average masses from 105 to 111 a.m.u. In the previous analysis, the comparison between gamma-ray energy spectra and statistical model calculations showed that a sharp cut-off approach of the gamma emission allowed to reproduce the data using values ranging between $E^* \approx 220$–230 MeV for the different ToF bins. However, the high excitation energy of the hot system populated in the reaction did not allow to extract any conclusion on the shape of the cut-off.

In the present analysis, gamma-ray spectra were compared to statistical model calculations assuming a Lorentzian shape for the GDR with a centroid energy $E_{\mathrm{GDR}} = 15$ MeV, a width $\Gamma_{\mathrm{GDR}} = 13$ MeV and a strength equal to 100% of the Thomas–Reiche–Kuhn (TRK) sum rule. A smooth cut-off, using the same parameters adopted in the Fermi function to reproduce 270 MeV and 330 MeV excitation energy data, was used. The calculations reproduce rather well all the three spectra as shown in Fig. 3 (a) giving a coherent description of the quenching phenomenon up to $E^* = 430$ MeV.

Calculation using the phenomenological models, previously discussed, were also performed and fail to reproduce the data in a more pronounced way than observed in the comparison with 330 MeV data.

A more quantitative evaluation of the progressive quenching of the GDR as a function of the excitation energy has been carried out comparing the GDR gamma multiplicity obtained integrating the experimental gamma spectra and the model predictions in the energy range between 12 and 20 MeV where the GDR yield is mainly concentrated. The LNS data up to $E^* = 330$ MeV are shown as full circles in Fig. 3 (b) as a function of excitation energy per nucleon. Data at 37A MeV are shown as full triangles. The different lines describe the trend of the results of each model prescription. The comparison between data and yields extracted from standard statistical model calculations connected by a solid black line shows that the onset of the quenching appears above $E^*/A = 1.5$ MeV.

The gap between the two data set reflects the different mass and charge of the nuclei populated in the reactions which influence the NZ/A factor of the decay width formula for statistical E1 gamma decay. In order to remove this dependency, the ratios between experimental and standard statistical model yields for each excitation energy per nucleon were calculated. The same approach was used to compare model predictions with data. Results are shown in Fig. 3 (c). Above $E^*/A = 1.5$ MeV, a smooth decreasing trend

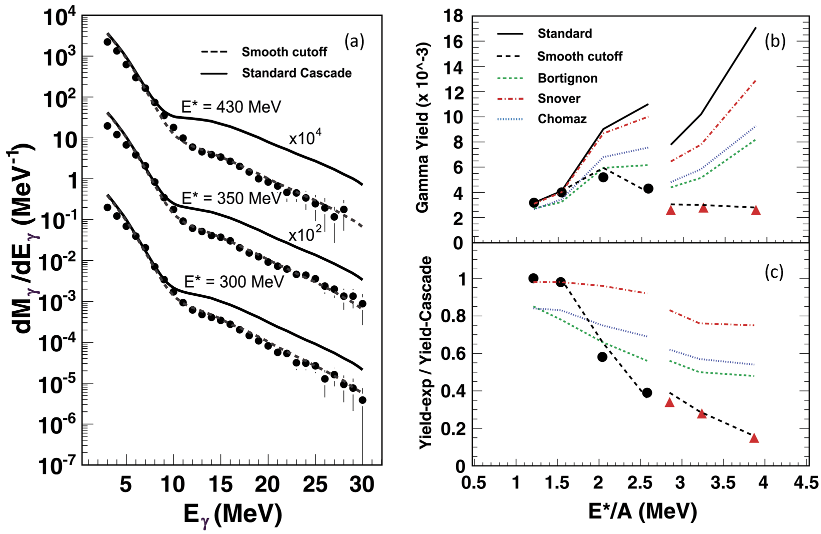

Fig. 3. (a) Gamma-ray energy spectra measured in the reaction ^{36}Ar + ^{98}Mo at 37A MeV are compared to smooth cut-off predictions shown as dashed lines [25]. (b) GDR gamma-ray multiplicities integrated in the region 12–20 MeV as a function of excitation energy per nucleon for the full data set. Full circles and triangles correspond to the LNS experiment data presented in this paper and to 37A MeV GANIL data, respectively. Different lines correspond to model predictions shown as a comparison. (c) Ratio of the experimental gamma multiplicity to the standard statistical model calculations shown as solid lines in panel (b) as a function of excitation energy per nucleon. Different line types correspond to the ratio between multiplicities extracted from model predictions and standard statistical model.

in the data is observed indicating a progressive increase of the quenching which appears to set in around 2 MeV excitation energy per nucleon. The smooth cut-off calculations nicely reproduce the overall trend indicating that the quenching phenomenon is rather sharp, the GDR fully disappearing between 200 MeV and 300 MeV excitation energy .

6. Conclusions

A study of the evolution of the GDR properties as a function of excitation energy in nuclei of the mass region $A \sim 120$–132 has been undertaken. The comparison with standard statistical model calculations shows that a quenching effect appears above $E^* = 200$ MeV and becomes progressively more important with increasing excitation energy. Phenomenological models are not able to reproduce the shape of the quenching up to high excitation energies. However, from the comparison of the spectral shapes, it is clear that such an effect can be better explained in terms of yield suppression and not as a progressive broadening of the width. The best description of the data is obtained using a smooth cut-off built using a Fermi function with 20 MeV diffuseness and 225 MeV for E_{cut} suggesting that the GDR quenching is a rather sharp effect.

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