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DAPNIA/SPhN 95-41

08/1995

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Soumis à Nuclear Physics A

The Giant Dipole Resonance in Hot Sn Nuclei

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Abstract :

We have studied the Giant Dipole Resonance (GDR) built on the excited states of ^{112}Sn formed in the fusion of ^{19}F with ^{93}Nb . The excitation energy of the compound nucleus ^{112}Sn was 130 and 152 MeV. High-energy γ -rays were detected in a 7-element BaF_2 cluster and 4 NaI(Tl) scintillators. Coincidences with the evaporation residues detected in two parallel-plate avalanche-counters ensured that the γ -rays were associated with fusion events. In order to study the characteristics of the GDR, we have performed analyses of the γ -ray spectra within the statistical model, using a continuous evolution of the GDR centroid energy with the mass and the temperature of the emitting nucleus, and a nuclear temperature dependent level density parameter. The theoretical prescriptions concerning the evolution of the GDR width with excitation energy have been tested. We show that, in order to reproduce the γ -spectra, the increase of the width must be more rapid than the two theoretical predictions. The width has to reach large values, of the order of 15 to 20 MeV above 100 MeV of excitation energy. These values are greater than the saturation value of about 12 MeV which has been published following the analyses using constant parameters. On this condition, the shape of the spectra can be reproduced with or without a saturation of the width. It is therefore not possible to say if the increase of the width is due to angular momentum effects or to collisional effects.

Keywords: Nuclear reactions $^{93}\text{Nb}(^{19}\text{F}, \gamma\text{-fusion residue})$, $E = 157, 183$ MeV; measured γ -rays spectra. Statistical model, Sn deduced Giant Dipole Resonance parameters, evolution with excitation energy.

1. Introduction

The study of the Giant Dipole Resonance (GDR) in hot nuclei is a unique tool to extract information on the nuclear structure at high temperatures and high angular momenta. The existence of the GDR built on low-lying excited states was revealed by radiative capture reactions (p, γ) on light nuclei [1–4]. The first quantitative analysis of high-energy γ -ray spectrum from statistical decay was carried out in 1974 by Dietrich et al. [5], for γ -rays emitted after the spontaneous fission of radioactive ^{252}Cf . In 1981 Newton et al. [6] observed γ -rays emitted from the GDR during the decay of hot nuclei formed in heavy-ion induced fusion reactions. This observation led to a considerable number of experimental and theoretical efforts in the study of hot nuclei [7–9].

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The GDR is a collective oscillation of the protons against the neutrons which can be microscopically described as a coherent superposition of 1p-1h excitations. It is damped either by direct γ or particle emission, or through the coupling to the complex compound nucleus states leading to the thermalization of the nucleus. For the GDR built on the ground state of heavy nuclei, the latter process is dominant and occurs on a time scale given by the GDR width ($\sim 10^{-22}s$). In the reverse process, which is concerned in the present fusion reactions, this allows the dipole states to be excited in $\sim 10^{-22}s$. From a theoretical point of view, it is not clear whether this coupling time remains constant with increasing nuclear temperature [10–12] or it becomes shorter [13, 14]. Anyway, $10^{-22}s$ is shorter than the life time of the compound nucleus, at least for temperatures below 4 MeV [10] since the life time of the compound nucleus stands around $10^{-18}s$ at a temperature of 1 MeV and $10^{-21}s$ at 3 MeV [15]. The relative probability of γ and particles emission lies around 10^{-3} per nuclear decay. As the GDR couples to the surface degrees of freedom and its response function reflects the nuclear deformations, its decay provides information on the shapes and fluctuations of the states on which it is built (see sect. 4.2).

The properties of the GDR built on excited states of nuclei have been essentially investigated for Sn isotopes formed in heavy-ion induced fusion reactions [16]. The experimental results for these isotopes are presented in Figs. 1 to 3. The evolution of the GDR centroid energy with the Sn excitation energy (Fig. 1) is rather weak since its value at an excitation energy $E^*=130$ MeV is less than 1.5 MeV below the ground state value (~ 16 MeV). The GDR width (Fig. 2) increases regularly up to $E^*=130$ MeV and then it saturates at a value of ~ 12 MeV. The saturation of the width was attributed to the saturation of the maximum angular momentum leading to fusion [16] which occurs at $E^* \sim 110$ MeV (Fig. 3). All these results were deduced from analyses of the γ -ray spectra performed within the statistical model, assuming that the GDR width, the GDR centroid energy and the level density parameter were constant throughout the compound nucleus decay chain. However, in the decay sequence, γ -rays are emitted not only by the initial compound nucleus but also by the daughter nuclei having different temperatures and angular momenta. Thus, in order to get really the characteristics of the GDR in the compound nucleus Sn, one has to take into account in the analysis the evolution of these characteristics all along the chain.

In this paper we present an analysis of the γ -ray spectra obtained from the decay of ^{112}Sn at excitation energies of 130 and 152 MeV, using a continuous evolution of the GDR centroid energy with the mass and the temperature of the emitting nucleus and a nuclear temperature dependent level density parameter. We test the different theoretical prescriptions concerning the evolution of the GDR width with excitation energy.

2. Experiments

The experiments were performed at the post-accelerated tandem of Saclay. 580 and 895 $\mu\text{g}/\text{cm}^2$ ^{93}Nb (99.9%) targets were bombarded with a ^{19}F beam at incident energies of 157.3 and 183.7 MeV, respectively. The beam consisted of ~ 1 ns wide bunches with 74 ns bunch separation and was

measured in a Faraday cup shielded with lead and paraffin in order to reduce the background due to γ -rays and neutrons.

The high-energy γ -rays were detected in a cluster of 7 (6.3 cm $\varnothing$ x 12.5 cm) hexagonal crystals of BaF₂ located at 24 cm from the target and at in-plane laboratory angles of 90° et 77° relative to the beam direction in the two experiments respectively. In the experiment carried out with the 183.7 MeV beam, we also used 4 NaI(Tl) scintillators (15.2 cm $\varnothing$ x 20 cm) located at 70 cm from the target and at in-plane laboratory angles of 57.5°, 73°, 106° and 137° relative to the beam direction. The solid angle covered by the BaF₂ cluster is equal to 2% of 4π assuming that the BaF₂ has an absolute efficiency equal to 0.85 for the γ -rays with energy greater than 5 MeV. The solid angle of each NaI(Tl) scintillator is equal to 0.14% of 4π with an efficiency of 0.6. The BaF₂ and NaI(Tl) detectors were surrounded by a 3mm thick lead shield which reduced the counting rate due to low energy γ -rays ($E_\gamma \lesssim 1$ MeV) to 50% and stopped the charged particles. Discrimination of γ -rays and neutrons was ensured by a measurement of the time of flight relative to the beam burst. The reaction products were detected in two position sensitive parallel plate avalanche counters PPAC (15×6 cm²) placed in-plane, symmetrically on each side of the beam at 70 cm from the target and covering an angular range lying between 2.9° and 15.1° which corresponds to nearly the whole angular distribution of the residual nuclei. They provided the energy loss and the time of flight relative to the BaF₂ crystals of the nuclei.

Gamma-rays or neutrons in coincidence with a reaction product were registered, provided the deposited energy in the whole BaF₂ cluster or in each NaI(Tl) was greater than ~ 5 MeV. The number of pileup events was estimated to be 0.7% for the BaF₂ cluster and 0.01% for each NaI(Tl). These events were not eliminated. The percentage of fortuitous coincidences between a reaction product and a cosmic ray detected in the BaF₂ cluster was estimated at 0.4% in the energy interval $E_\gamma = [0, 8]$ MeV, 1.5% in $E_\gamma = [8, 15.8]$ MeV and 4% in $E_\gamma = [15.8, 24]$ MeV. It is found to be negligible in the case of the NaI(Tl) because of their small volume.

The energy calibration of the γ -rays was obtained using the sources ⁶⁰Co ($E_\gamma = 1.17, 1.33$ MeV), ⁸⁸Y ($E_\gamma = 0.898, 1.836$ MeV) and the composite sources of ²⁴¹Am+⁹Be (⁹Be (α, n)¹²C*, $E_\gamma = 4.43$ MeV) and of ²³⁸Pu+¹³C (¹³C (α, n)¹⁶O*, $E_\gamma = 6.13$ MeV).

The fusion induced events were selected off-line in the 2-dimensional spectrum (energy loss,time of flight) of the reaction products. This spectrum for the nuclei in coincidence with γ -rays detected in the BaF₂ cluster is presented in Fig. 4. Events located inside the contour (dashed line) were accepted.

The probability of detecting simultaneously more than one γ -ray of the compound nucleus decay chain in the BaF₂ cluster is $\sim 7\%$. In order to take this into account, we treated the data of the BaF₂ cluster by investigating the position of the fired detectors. If the fired detectors were neighboring we assumed that only one γ -ray was detected in the whole cluster and its energy was reconstructed by summing the deposited energy in each detector. If the fired detectors were isolated or if they formed small clusters located far from one another we assumed that one γ -ray of the cascade was detected in

each isolated detector or in each small cluster and the energy of each γ -ray was reconstructed. The probability to detect two different γ -rays in neighbouring detectors was small ($< 2\%$).

At beam energies of 157.3 MeV and 183.7 MeV, the incomplete fusion cross section must represent around 20% and 30% respectively of the total fusion cross section [17]. The corresponding events are included in the contour of Fig. 4, thus, in order to test their influence on the γ -ray spectra we selected the events located inside a narrow window centered on the compound nucleus time of flight. The associated γ -ray spectra were identical to the spectra corresponding to all the events inside the contour, showing that the spectra are insensitive to the presence of incomplete fusion.

The γ -ray spectra were corrected for Doppler shift and presented in the center of mass system, assuming emission from a source moving with the velocity of the center of mass. In Fig. 5, we show the γ -ray spectra obtained with the BaF₂ cluster at $E^*=130$ MeV and $E^*=152$ MeV and in Fig. 6 the spectrum of the BaF₂ cluster (solid line) is compared with the NaI(Tl) spectra (points) at $E^*=152$ MeV. BaF₂ spectra have been normalized to NaI spectra at 6 MeV. The data are very similar. However, the high-energy cross-section is smaller in the NaI(Tl) spectra than in the BaF₂ one. This is partly due to an electronic rejection of the most rapid residual nuclei for the coincidence events associated to NaI(Tl) crystals. The rejection corresponds to about 2% of the events. An other reason for the discrepancy may be that the emission of dipole γ -rays from a deformed system is anisotropic in the center of mass system. The anisotropy varies with the angular momenta of the nuclei in the decay chain. For example, in the case of Sn, the anisotropy coefficient varies from -0.05 for $J \sim 34\hbar$ to -0.2 for $J \sim 48\hbar$ [18].

3. Statistical model

The spectra were analysed assuming that the γ -rays originated from a completely equilibrated system, the compound nucleus, and we modified an extended version of the statistical de-excitation code CASCADE [19, 20].

The main equations of the statistical model are very briefly recalled in the following. The decay rate for emitting a particle x from an excited nucleus 1 (excitation energy E_1 , spin J_1 parity π_1) to a nucleus 2 (excitation energy E_2 , spin J_2 parity π_2) is given by :

$$R_x d\varepsilon_x = \frac{1}{2\pi\hbar} \frac{\rho_2(E_2, J_2, \pi_2)}{\rho_1(E_1, J_1, \pi_1)} \sum_{S=|J_2-s_x|}^{S=J_2+s_x} \sum_{L=|J_1-S|}^{L=J_1+S} T_L^x(\varepsilon_x) d\varepsilon_x \quad (1)$$

where $\varepsilon_x = E_1 - E_2$ - separation energy is the kinetic energy of the particle x , s_x is its spin, L is its orbital angular momentum and $\vec{S} = \vec{J}_2 + \vec{s}_x$ is the channel spin. $T_L^x(\varepsilon_x)$ is the transmission coefficient of the particle x , ρ_1 et ρ_2 are the level densities of the initial and daughter nucleus respectively. The transmission coefficients $T_L^x(\varepsilon_x)$ are obtained from the analysis of elastic scattering experiments using the optical model.

The decay rate for emitting a γ -ray of multipolarity J is given by a formula similar to the previous one :

$$R_\gamma dE_\gamma = \frac{1}{2\pi\hbar} \frac{\rho_1(E_2, J_2, \pi_2)}{\rho_1(E_1, J_1, \pi_1)} \sum_{J=|J_1-J_2|}^{J=J_1+J_2} \xi_J f_J(E_\gamma) dE_\gamma \quad (2)$$

where $\xi_J f_J(E_\gamma)$ are energy dependent strengths.

4. Ingredients of the analysis

In the present analysis, emission of γ -rays from the GDR, the Isoscalar Giant Quadrupole Resonance (ISGQR) and the Isovector Quadrupole Giant Resonance (IVGQR) are taken into account. For the emission of magnetic dipole radiation we used a constant strength ξ_J [21] and an energy dependence $f_J(E_\gamma) = E_\gamma^{2J+1}$, which is the basic energy dependence for single particle transitions [22]. The other resonances are parametrized by a Lorentzian function. The decay rate associated to the GDR is given by the following relation :

$$R_\gamma dE_\gamma = 2.09 \times 10^{-5} \frac{1}{h} \frac{N Z}{A} \frac{\rho_1(E_2, J_2, \pi_2)}{\rho_1(E_1, J_1, \pi_1)} \frac{S_{GDR} \Gamma_{GDR} E_\gamma^4}{(E_\gamma^2 - E_{GDR}^2)^2 + E_\gamma^2 \Gamma_{GDR}^2} dE_\gamma \left(\frac{1}{s} \right) \quad (3)$$

and the decay rates associated to the ISGQR and IVGQR by:

$$R_\gamma dE_\gamma = 3.22 \times 10^{-11} \frac{1}{h} R^2 \frac{\rho_1(E_2, J_2, \pi_2)}{\rho_1(E_1, J_1, \pi_1)} C E_\gamma^4 dE_\gamma \left(\frac{1}{s} \right) \quad (4)$$

$$C = \frac{Z^2}{A} \times S_{ISGQR} \times LOR1 + \frac{NZ}{A} \times S_{IVGQR} \times LOR2$$

where

$$LOR1 = \frac{E_\gamma^2 \Gamma_{ISGQR}}{(E_\gamma^2 - E_{ISGQR}^2)^2 + E_\gamma^2 \Gamma_{ISGQR}^2}$$

$$LOR2 = \frac{E_\gamma^2 \Gamma_{IVGQR}}{(E_\gamma^2 - E_{IVGQR}^2)^2 + E_\gamma^2 \Gamma_{IVGQR}^2}$$

N , Z , A is the neutron, proton and mass number of the emitting nucleus and R is the nuclear uniform density radius. S_{GDR} , S_{ISGQR} , S_{IVGQR} are the percentages of the energy-weighted sum rules (EWSR) exhausted by the excitation of the GDR, ISGQR and IVGQR respectively. The EWSR which are used are:

$$\int_0^\infty \sigma_{GDR}(E_\gamma) dE_\gamma = 60 \frac{NZ}{A} (mb \cdot MeV) \quad GDR \quad (6)$$

$$\int_0^\infty \frac{\sigma_{ISGQR}(E_\gamma)}{E_\gamma^2} dE_\gamma = \frac{\pi^2}{5} \frac{e^2}{\hbar c} \frac{1}{Mc^2} \frac{Z^2}{A} R^2 \left(\frac{fm^2}{MeV} \right) \quad ISGQR \quad (7)$$

$$\int_0^\infty \frac{\sigma_{IVGQR}(E_\gamma)}{E_\gamma^2} dE_\gamma = \frac{\pi^2}{5} \frac{e^2}{\hbar c} \frac{1}{Mc^2} \frac{NZ}{A} R^2 \left(\frac{fm^2}{MeV} \right) \quad IVGQR \quad (8)$$

where $\sigma_{GDR}(E_\gamma)$, $\sigma_{ISGQR}(E_\gamma)$, $\sigma_{IVGQR}(E_\gamma)$ are the cross sections of the GDR, ISGQR and IVGQR excitation respectively.

As we have mentioned before, in all the previous analyses the characteristics of the resonances (energy, width, strength) were assumed to be constant throughout the decay chain of the compound nucleus. The level density parameter was constrained to be constant or to take two distinct values in the decay chain, $A/8 \text{ MeV}^{-1}$ and $A/12 \text{ MeV}^{-1}$ [16]. We introduced into CASCADE the continuous evolutions of the level density parameter and of the GDR characteristics which are described in the next paragraphs.

4.1 Level density parameter

For the level density parameter a we used the following dependence on the nuclear temperature T as proposed by Ormand et al. [23] :

$$a(T) = \frac{A}{\alpha(T)} \quad \text{with} \quad \alpha(T) = \frac{\alpha_0}{1 + 0.4 \exp \left[-\left(\frac{T}{3} \right)^2 \right]} \quad (9)$$

The exponential temperature dependence of a is due to small amplitude quantal fluctuations of the nuclear surface. The coefficient α_0 reflects large amplitude thermal fluctuations of the nuclear surface and it is relatively stable with the mass, the angular momentum and the temperature of the nuclei. In our case, $90 \lesssim A \lesssim 112$, $0 \lesssim J \lesssim 65\hbar$ and $0 \lesssim T \lesssim 3.6 \text{ MeV}$, following ref. [23] α_0 should vary from 11.6 to 12.3. A value of 12 MeV gives the evolution of $\alpha(T)$ displayed in Fig. 7. The corresponding behaviour of a , in the $A = 100$ region, is in good agreement with experimental results deduced from evaporated particle spectra [23, 24]. One sees on Fig. 8 than the use of a temperature dependent level density parameter rather than a constant one strongly influences the shape of the spectra and thus can not be omitted in the analysis.

4.2 GDR characteristics

As the centroid energy of the GDR built on the ground state has not been measured for every nucleus of the de-excitation chain, $90 \lesssim A \lesssim 112$, we parametrized this energy either with:

$$E = 76.5 A^{-1/3} \quad (10)$$

which is valid for the heavier Sn isotopes or with

$$E_{GDR}(A, T = 0) = 31.2 A^{-1/3} + 20.6 A^{-1/6} \quad (11)$$

which follows the mean evolution of the centroid energy over a large range of masses [25, 26].

Following the theoretical predictions, the GDR centroid energy varies smoothly with the nuclear temperature since its value at 3 MeV is around 4–6% smaller than its ground state value [27–30]. We applied the evolution proposed by Lipparini and Stringari using a Fermi energy of 36 MeV [29] :

$$E_{GDR}(A, T) = E_{GDR}(A, T = 0)(1 - 3.86 \times 10^{-3} T^2) \quad (12)$$

We will see later (Fig. 12) that the spectrum is sensitive to the centroid energy of the GDR built on the ground state of nuclei. On the contrary, the coefficient of the temperature in the relation (12), for the variation of the energy with the temperature, could be varied by 25% without a visible effect on the spectrum.

Concerning the GDR width, there are two different theoretical approaches and a phenomenological one, which are presented in the following.

In the theoretical approach of Broglia et al., the GDR width can be approximated to the square root of a quadratic sum of three terms [31] as far as the adiabatic regime is concerned:

$$\Gamma_{GDR} = \sqrt{\Gamma_Q^2 + \Gamma_{0,\pm 1}^2 + \Gamma_T^2} \quad (13)$$

The term Γ_Q corresponds to the sequential coupling of the GDR to the 2p-2h, 3p-3h, ... np-nh configurations of the compound nucleus. In this coupling, the 2p-2h excitations play an important role since they serve as “doorway states” towards the complete thermalization. They account for most of the term Γ_Q [31–35]. According to Bortignon et al. [10, 11] and authors of ref [12, 36], Γ_Q is essentially independent of the temperature of the system. In [36], microscopic calculations including particle-particle and particle-hole interactions to all orders of perturbation for ^{16}O and ^{40}Ca lead to a Γ_Q term constant with temperature. However, following the authors of these calculations, some temperature dependence may occasionally be found for other nuclei .

For heavy nuclei, Γ_Q represents $\sim 85\%$ of the ground state width [7, 37]. As in the present analysis the emitting nuclei have masses $90 \lesssim A \lesssim 112$, Γ_Q varies between 4 and 6 MeV. Due to the lack of photoabsorption data for many nuclei in the cascade, we used 4.8 MeV which is taken theoretically in the Sn region.

At a given excitation energy of a nucleus, the spins of the different states are distributed from $0\hbar$ to a maximum value J_{max} . Each spin induces a different deformation of the nucleus. The coupling of the GDR to the nuclear surface leads to a splitting of the dipole strength and gives a contribution to the total width equal to the term $\Gamma_{0,\pm 1}$ [31].

$$\Gamma_{0,\pm 1} \sim 2.3\beta E_{GDR}(A, T) \quad (14)$$

$$\beta = \sqrt{\frac{5\pi}{4}} \frac{2.1 A^{-\frac{1}{3}} J^2}{1 - 0.0205 \frac{Z^2}{A}}$$

where β is the deformation parameter and J the nuclear spin.

Due to the finite size of the system, the temperature induces large amplitude thermal fluctuations of the nuclear surface and consequently a splitting of the dipole strength. The contribution to the total width coming from these fluctuations is equal to the term Γ_T with

$$\Gamma_T \sim 3\sqrt{T} \quad (15)$$

in the Sn region [31].

In the approach proposed by Di Toro et al., the damping of the GDR is studied in a semiclassical approach solving a Vlasov equation with a collision relaxation time. Temperature effects are introduced in the initial distribution function and in Pauli blocking rearrangement in the path to equilibration. The authors [13, 14, 38] obtain an continuous increase of the width with temperature due to the enhancement of nucleon-nucleon collisions. The last calculation of the evolution of the GDR width with the excitation energy of the nucleus [38] lies fairly well with the parametrization found in low energy data analysis [39]:

$$\Gamma(E^*) = \Gamma_0 + 0.0026 E^{*1.6} \quad (16)$$

where Γ_0 is the width of the GDR built on the ground state (dashed-dotted line in Fig. 13).

In these theories, one assumes that the GDR is not excited during the first steps of the collision and that the time that it needs to be excited is $\hbar/\Gamma_Q$. At low temperature, the GDR is assumed to exhaust 100% of the TRK sum rule (Eq. (6)) but as the life time of the nucleus becomes shorter with increasing excitation energy, the GDR would not have time to be excited and there would be a progressive reduction of the GDR strength with increasing excitation energy. This is taken into account by multiplying the decay rate for dipole γ -ray emission (Eq. 3) by a factor $\Gamma_{LT} = \Gamma_Q/(\Gamma_Q + \Gamma_{evap})$, where Γ_{evap} is the width of particle evaporation [10]

Kasagi et al. [40, 41] reproduce spectra corresponding to the γ -decay of nuclei with A around 120 and E^* up to 600 MeV with the following parametrization when Γ_{LT} is not introduced in the calculation (dashed line in Fig. 13):

$$\Gamma(E^*) = 4.8 + 0.035 E^* + 1.6 \times 10^{-8} E^{*4} \quad (17)$$

and with the evolution of Eq. (16) when Γ_{LT} is taken into account [42].

As the evolutions proposed by Kasagi et al. and by Di Toro et al. are independent of the angular momentum, the width takes a unique value at each excitation energy.

4.3 IVGQR and ISGQR characteristics

The tail of photoabsorption cross section for nuclei with $A \sim 100$ is generally not fully reproduced with a single Lorentzian exhausting 100% of the GDR EWSR. In Fig. 9 the stars represent the photoabsorption cross section in the case of ^{118}Sn [25]. It is evident that a single Lorentzian (dotted line) cannot reproduce the experimental data at energies above 18 MeV. The data are well reproduced by the sum of two Lorentzians (solid line). The second Lorentzian (dashed line) is located at 22 MeV, its width is equal to 10 MeV and it exhausts 500% of the classical IVGQR EWSR (Eq. 8) multiplied by an empirical function given as :

$$c = \frac{1}{1 + \exp(E_\gamma - 28)} \quad (18)$$

This percentage is in good agreement with theoretical predictions of Urbas and Greiner concerning the ^{118}Sn [43, 44]. In the following, all the calculations have been carried out assuming that the photoabsorption cross section in excess above 18 MeV is due to the IVGQR decay. Due to the lack of data, the excess has been supposed identical for all the nuclei with $A \sim 100$. Since very little is known about the IVGQR, its parameters were kept constant.

For the ISGQR we used a Lorentzian located at 13.1 MeV, having a width equal to 3.2 MeV and exhausting 50% of the ISGQR EWSR [45]. However, its contribution to the spectra is negligible.

4.4 Other ingredients

A maximum angular momentum equal to $63\hbar$ was taken for fusion at the two excitation energies of the compound nucleus (see Fig. 3 and [46, 47]). For the other parameters of the calculation, we used the standard systematics proposed in the code CASCADE.

Different mechanisms may feed the γ -spectra at energy $E_\gamma > 20$ MeV, such as the nucleon-nucleon bremsstrahlung, the nucleus-nucleus bremsstrahlung or even the quasideuteron mechanism [48]. At the present incident energies, these mechanisms affect in a small way the GDR energy region. According to our estimation, the nucleon-nucleon bremsstrahlung which must be dominant, should represent about 15% of the γ -spectra at $E_\gamma = 20$ MeV. We have neglected this contribution in the analysis.

5 Results of the analysis and discussions

The spectra from CASCADE were folded with the experimental set-up response function using the Monte Carlo shower code GEANT3 [49]. Figure 10 presents a spectrum obtained with CASCADE (1) and the same spectrum folded with the experimental set-up response function of the BaF_2 cluster (2).

For the comparison between the theoretical spectra and the data, in order to allow a representation in a linear scale, all the spectra have been divided by $\exp(-0.305E + 10.85)$ at $E^* = 130$ MeV and $\exp(-0.305E + 10.95)$ at $E^* = 152$ MeV. The normalization between the theory and the data points was done in the low part of the spectra where the parameters of the GDR have no influence on the

calculations. Finally, the statistical fluctuations of the theoretical spectra have been averaged over a width increasing with the energy (about 1 MeV at $E_\gamma = 20$ MeV).

In the first part of this section, we will test the different prescriptions concerning the width of the GDR, using all the ingredients of section 4. The calculations will be compared to the BaF_2 data. In the second part, we will discuss analyses using constant parameters.

5.1 Test of the different evolutions of the GDR width.

5.1.1 Evolution proposed by Broglia et al. Dotted lines in Fig. 11a,b,c display the comparison between the data (points) and the calculated spectra using the Eq. (13) to (15) for the width. The parameter α_0 of the level density distribution is equal to 12, the centroid energy follows $76.5A^{-1/3}$ and the maximum angular momentum of fusion is equal to $63\hbar$ at the two excitation energies. The correction due to Γ_{LT} is not taken into account. One notes that the calculations strongly overestimate the cross-section in the region of the resonance. In order to see the influence of the maximum angular momentum on the spectra, the calculation has been done with J_{max} equal to $85\hbar$ which is the maximum angular momentum that a nucleus with a mass around 110 can sustain according to the rotating-liquid-drop model [50]. In this case, fission has been included in the decay chain. Solid lines in Fig. 11a show that the effect is noticeable but not large enough to reproduce the data. Fig. 11b shows the sensitivity of the calculation to the $\Gamma_{0,\pm 1}$ term of the width. If the constant in Eq. (14) is increased by 28% (from 2.3 to 2.9, dashed-dotted curve) or by 56% (from 2.3 to 3.6, dashed curve), the agreement is gradually improved. When, in addition, one takes into account the Γ_{LT} correction with $\Gamma_Q = 4.8 \text{ MeV}$, there is an overall agreement at $E^* = 130$ MeV and a small overestimation (less than 10%) at $E^* = 152$ MeV (solid lines). The sensitivity to the Γ_T term is displayed in Fig. 11c. For the dashed-dotted curve, the constant in Eq. (15) has been increased by 56% (from 3. to 4.68). This has the same effect that an equivalent variation of $\Gamma_{0,\pm 1}$ (dashed curve Fig. 11b). However, the effect is non linear and one has to increase the constant by 100% and to take into account the Γ_{LT} term to obtain a good agreement at $E^* = 130$ MeV. It subsists a small overestimation at $E^* = 152$ MeV (solid lines Fig. 11c). This figure reveals the ambiguity between the $\Gamma_{0,\pm 1}$ and the Γ_T terms of the width. The degree of freedom on the Γ_Q term is estimated to be smaller (about $\pm 10\%$) and thus is not discussed.

In figure 12, the sensitivity to the value of the level density parameter α_0 and to the evolution with the mass of the centroid energy at $T=0$ is shown. The reference spectra are the solid lines of Fig. 11b for which $\alpha_0 = 12$ and $E_{GDR}(A, T=0)$ follows Eq. (10). The other curves correspond to different cases for which $\alpha_0 = 11.5$ or 12 and $E_{GDR}(A, T=0)$ follows Eq. (10) or Eq. (11). The details of the calculations are described in the caption of Fig. 12. One sees that the effect of these changes is small at $E^* = 130$ MeV and somewhat larger at $E^* = 152$ MeV. However, the differences between the curves are not sufficient to put strong constraints on these parameters or to strongly influence the discussion concerning the width.

Figure 13 presents the width versus the excitation energy of ^{112}Sn . The thick dashed line represents the strict application of the theory of Broglia whereas the solid line and the thick solid line correspond to the best fits of Fig. 11b and 11c where the $\Gamma_{0,\pm 1}$ and the Γ_T terms of the width have been increased. For the three curves, the GDR is supposed to be built on states with the mean angular momentum $\langle J \rangle = 2/3 J_{max}$ of fusion. The saturation of the solid line and the change in the slope of the thick solid line are due to the saturation of J_{max} . One notes first, that in the domain in which we are the most sensitive: from 80 MeV to 150 MeV of excitation energy, these two solid curves are very similar, they differ by less than 0.7 MeV. Secondly, the difference between them and the thick dashed curve increases from 2 MeV at $E^* = 50$ MeV to 4 MeV at $E^* = 150$ MeV. This seems to indicate that some effect is not taken into account in the theory of Broglia et al. The evolutions corresponding this time to the maximum and the minimum angular momenta at each excitation energy, again for the best fits of Figs. 11b and 11c, are displayed in Figs. 14a and 14b. One sees that in the two cases, the width reaches values larger than 20 MeV and that at a given excitation energy, the distribution of the width is very large. However, if the evolutions associated to the mean angular momentum are similar, the envelopes of the width are notably different which proves that the spectra are mainly sensitive to the mean evolution of the width. In the same connection, it is interesting to study the probability of the emission of dipole γ -rays with increasing nuclear spin. To this end we calculated the cross section of γ -rays with energy $E_\gamma > 8 \text{ MeV}$ versus the nuclear spin, for the compound nucleus ^{112}Sn at $E^* = 130$ MeV and for the daughter nuclei ^{111}Sn , ^{110}Sn , ^{109}Sn at $\langle E^* \rangle = 114$ MeV, 104 MeV, 91 MeV, respectively. The distribution is centered at $50\hbar$ with a FWHM equal to $10\hbar$ for $J_{max} = 63\hbar$. This has to be compared to the mean angular momentum which is equal to $42\hbar$.

In summary, we have shown that one can reproduce our data with the theory of Broglia et al. provided that the mean value of the width is increased by 2 to 4 MeV depending on the excitation energy. For that, it is necessary to increase by more than 50% the contribution of one or the other terms of the width. This strong increase does not seem realistic regarding the underlying physics. To our point of view, it would simulate some effect which would not be taken into account in this theory. The uncertainties existing on the different parameters such as $a(T)$, J_{max} and $E_{GDR}(A, T = 0)$ are not able to much alter this conclusion.

5.1.2 Evolution proposed by Di Toro et al.

Solid lines in figure 15 show the result of the calculations when using the evolution of Di Toro et al. for the width (Eq. (16) and dashed-dotted lines in Fig. 13) and including the correction for the life time Γ_{LT} with $\Gamma_Q = \Gamma_{GDR}$. The parameter α_0 is equal to 12, the centroid energy follows $76.5A^{-1/3}$ and J_{max} equal $63\hbar$ at the two excitations energies. The calculations strongly overestimate the cross-section in the GDR region at the two excitation energies. As in the case of the theory of Broglia et al., the agreement is not much improved by increasing J_{max} to $85\hbar$ (dashed-dotted lines).

In the same figure are shown, as dashed lines, calculations with the previous parametrization [14]:

$$\Gamma(E^*) = E_0 + 0.07E^* + 0.710^{-8}E^{*4} \quad (19)$$

which corresponds to a much more rapid increase of the width with excitation energy (dotted line in Fig. 13). The life time correction is taken into account. Following the authors of ref. [38] this evolution was too rapid. However, one can see that the agreement with the data is much better than with the new evolution (solid lines), confirming that one needs large width to reproduce the data. Considering the great difference between the results of the calculations with the two parametrizations and the uncertainties on the other parameters ($a(T)$, $E_{GDR}(A, T = 0)$, J_{max}), it is clear that one could reproduce the data with a continuous increase of the width that is without assuming any saturation.

5.1.3 Kasagi et al. parametrization The parametrization of Kasagi et al. (Eq.(17)) leads also to a large overprediction of the cross section in the GDR region for both the two excitation energies of ^{112}Sn (Fig. 16). The corresponding evolution of the width is displayed as dashed line in Fig. 13. The fact that the theoretical bump in the GDR region is too pronounced indicates, as for the more recent parametrization of Di Toro (dashed-dotted lines in Fig.13), that the width of the GDR is not large enough.

5.2 Comparison with the results of analyses using constant width

The values of the width obtained until now by doing analyses using constant parameters are displayed in the Fig. 13 (squares and stars). They are smaller than the mean values that we find with our analysis (solid and thick solid lines in Fig. 13). This is partly not surprising since the value of the width obtained for Sn at a given excitation energy in the previous analyses is averaged over the temperature, the mass and the angular momentum of all the emitting nuclei in the decay chain.

The evolution of the GDR centroid energy with the excitation energy of ^{112}Sn used in the present analyses is compared in Fig 1 (solid line) with the results previously published (points). They are compatible, nevertheless, this is not really significant since the sensibility of the calculations to the slope of this evolution is very small (cf. section 4.2)

Two sets of data are not directly comparable since the corrections due to the experimental set-up are different. Thus, in order to compare our data at $E^*=130$ MeV with the data obtained at the same excitation energy by Chakrabarty et al. [39] we have done an analysis using constant parameters in the decay chain. Fig. 17 shows that our data are well reproduced using :

$$\begin{aligned} \Gamma_{GDR} &= (12 \pm 1) \text{ MeV}, \quad E_{GDR} = (15.5 \pm 0.5) \text{ MeV} \\ a &= \frac{A}{\alpha} \text{ MeV}^{-1} \quad \text{with} \quad \alpha = 12 \pm 0.5 \end{aligned} \quad (20)$$

This value of the width is reported in Fig. 13 as a circle. The results of Chakrabarty et al. are the following :

$$\Gamma_{GDR} = (10.8 \pm 0.6) \text{ MeV}, E_{GDR} = (14.6 \pm 0.4) \text{ MeV}$$

$$a = \frac{A}{\alpha} \text{ MeV}^{-1} \quad \text{with} \quad \alpha = 9 \pm 1 \quad (21)$$

The difference concerns essentially the value of the level density parameter and reflects a difference of the experimental data since the influence on the spectra of this parameter is not negligible particularly at high energy. The discrepancy is probably due to the fact that in the previous work the use of a multiplicity filter to enhance the fusion events among the event triggers caused a rejection of fusion events populating low spins. CASCADE calculations show that the rejection of these events results in an inhibition of the cross section in the GDR region.

6. Conclusion

We have measured the γ -ray spectra of de-excitation of the compound nucleus ^{112}Sn formed with 130 and 152 MeV of excitation energy, selecting accurately the residue of fusion events. In order to analyse the data, we have modified the code CASCADE using the most recent theoretical developments. We have introduced into CASCADE a continuous evolution of the level density parameter with nuclear temperature and an evolution of the GDR centroid energy with nuclear mass and temperature. Three different evolutions of the GDR width with excitation energy of the emitting nucleus have been tested.

We have shown that the use of a temperature dependent level density parameter rather than a constant one gives rise to a great change of the shape of the γ -ray spectra and can not be neglected. The uncertainties on the evolution of the level density parameter and of the centroid energy at $T=0$ with the mass of the nuclei influence the results but do not change the conclusions concerning the width of the GDR.

The point that we want to stress, is that the spectra can be reproduced with or without a saturation of the width providing that it reaches large values, of the order of 15 to 20 MeV, above 100 MeV of excitation energy. These values have to be compared to the saturation value of about 12 MeV which has been published following analyses using constant parameters. It is not possible to infer if the increase of the width with excitation energy is due to angular momentum effects or to collisional effects because the strict application of the two existing theories does not allow to reproduce the data. It seems that there is a missing effect in the description of the different terms of the width in the theory of Broglia et al. On the other hand, the increase of the width corresponding to the last parametrization of Di Toro et al. is clearly too slow.

More constraining experiments are needed in order to probe deeply the evolution of the width. Spectra measured at higher excitation energies should be more sensitive to this evolution. However, new problems arise as the excitation energy increases, such as the knowledge of the excitation energy of the compound nuclei formed by deep inelastic or incomplete fusion and the presence of a large

bremsstrahlung contribution. It appears also conceptual difficulties with the validity of the statistical model since the decay time becomes of the same order as the time needed for the thermalization. Considering all that, it seems that the point should be to prove more clearly the role played by thermal and angular momentum effects in the low excitation energy region ($E^* \lesssim 200$ MeV) where all these points are still under control. A first experiment of this type studying the GDR in Sn around $E^*=85$ MeV claims that the increase of the width is due to the increase of the angular momentum [51]. New experimental results concerning γ -ray measurements in coincidence with selected channels could also help to disentangle the different effects [52, 53].

We are grateful to P. F. Bortignon for his help during the theoretical analysis. We would like to thank M. Di Toro and C. Beck for useful discussions and M. N. Harakeh for supplying us with the initial version of the *CASCADE* code.

Figure 1 Evolution of the GDR centroid energy with the excitation energy of Sn isotopes from analyses using constant parameters for the GDR (squares and stars). Solid line: evolution used in this paper.

Figure 2 Evolution of the GDR width with the excitation energy of Sn isotopes from analyses using constant parameters for the GDR (squares and stars). Solid line: parametrization of this evolution.

Figure 3 Maximum angular momentum leading to fusion versus the excitation energy of Sn isotopes.

Figure 4 2-dimensional spectrum (ΔE , t) of the residual nuclei at $E^*=152$ MeV (coincidence events between a γ -ray detected in the BaF_2 cluster and a reaction product). The events located inside the contour were accepted in the analysis.

Figure 5 γ -ray spectra in the center of mass system obtained with the BaF_2 cluster.

Figure 6 Comparison of the γ -ray spectrum obtained with the BaF_2 cluster (solid line) and the NaI(Tl) spectra (points) at $E^*=152$ MeV in the center of mass system. The BaF_2 spectrum has been normalized to the NaI(Tl) spectra at 6 MeV.

Figure 7 Evolution with the temperature of the parameter $\alpha(T)$ given by the relation (9) using $\alpha_0 = 12 \text{ MeV}$.

Figure 8 Comparison between calculations where a was equal to $A/9$ and $A/11 \text{ MeV}^{-1}$ (dashed and dotted lines respectively) throughout the decay chain and a calculation where we used a temperature dependent a following the relation (9) (solid line). The spectra are normalized at 6 MeV.

Figure 9 Photoabsorption data obtained for the ^{118}Sn (stars). The GDR is parametrized with a Lorentzian (dotted line) located at 16 MeV and the cross section in excess above 18 MeV with a second Lorentzian (dashed line) multiplied by an empirical function. The solid line represents the sum of the Lorentzians.

Figure 10 Theoretical spectrum (1) and theoretical spectrum folded with the experimental set-up response function for the BaF_2 cluster (2).

Figure 11 Comparison of present data (points) with calculations using the theory of Broglia et al. (Eq. (13) to (15)). The parameter α_0 of the level density distribution is equal to 12, the centroid energy follows $76.5A^{-1/3}$. All the dotted lines correspond to $J_{\text{max}} = 63h$. Solid lines in Fig 11 (a): $J_{\text{max}} = 85h$, fission has been included in the calculation. Fig. 11b: the constant in Eq. (14) has been increased by 28% (from 2.3 to 2.9, dashed-dotted-curve), by 56% (from 2.3 to 3.6, dashed-curve). In addition, the Γ_{LT} term has been taken into account in the calculations represented by solid lines. Fig. 11c: the constant in Γ_T term (Eq. (15)) has been increased by 56% (from 3 to 4.68, dashed-dotted curves) and by 100% (from 3 to 6, solid lines). In the case of the solid lines the Γ_{LT} term has been included.

Figure 12 Comparison of present data (points) with calculations using the theory of Broglia et al. (Eq. (13) to (15)). Solid lines: reference spectra. It corresponds to solid lines of Fig. 11b for which $\alpha_0 = 12$ and $E_{GDR}(A, T = 0)$ follows Eq.(10). Dashed-dotted lines: $\alpha_0 = 11.5$, $E_{GDR}(A, T = 0)$ follows Eq.(10). Dashed lines: $\alpha_0 = 11.5$, $E_{GDR}(A, T = 0)$ follows Eq.(11). Dotted lines: $\alpha_0 = 12$, $E_{GDR}(A, T = 0)$ follows Eq.(11)

Figure 13 Comparison of the different evolutions of the width with the excitation energy of Sn nucleus. Thick dashed line: strict application of the theory of Broglia et al. Solid line and thick solid line: evolution of the width in the theory of Broglia et al. when $\Gamma_{0,\pm 1}$ and Γ_T are respectively increased (correspond to the best fits of Fig. 11b and Fig. 11c). For these three curves, calculations have been done, at each excitation energy, for a GDR built on states having the mean spin populated at this excitation energy. Dotted-dashed line and dotted line: evolutions of the width proposed by Di Toro et al., Eq. (16) and Eq. (19) respectively. Dashed line: phenomenological evolution given by Kasagi et al. Squares, stars : widths obtained in other experiments by doing analyses using constant parameters (see Fig. 2). Circle: width obtained in the analysis of our data using constant parameters.

Figure 14 Envelope of the width versus the excitation energy of ^{112}Sn in the theory of Broglia et al. At each excitation energy, the lower value gives the width of the GDR built on states with $J=0$ and the upper value the width of the GDR built on states having the maximum spin populated at this excitation energy. The intermediate value corresponds to the mean spin $\langle J \rangle = 2/3 J_{max}$. a) corresponds to the best fit of Fig. 11b where $\Gamma_{0,\pm 1}$ has been increased by 56%. b) corresponds to the best fit of Fig. 11c where Γ_T has been increased by 100%.

Figure 15 Comparison of present data with calculations using the evolution of the width proposed by Di Toro et al. $\alpha_0 = 12$, $E_{GDR}(A, T = 0)$ follows Eq.(10) Solid lines and dashed-dotted lines: Eq. (16) has been used with $J_{max} = 63\hbar$ and $85\hbar$ respectively. Dashed lines: Eq. (19) has been used with $J_{max} = 63\hbar$.

Figure 16 Comparison of present data with calculations using the phenomenological evolution of the width proposed by Kasagi et al. $\alpha_0 = 12$, $E_{GDR}(A, T = 0)$ follows Eq.(10), $J_{max} = 63\hbar$.

Figure 17 Fit of present data with calculations using constant parameters for the GDR and the level density parameter. $\Gamma_{GDR} = (12 \pm 1) \text{ MeV}$, $E_{GDR} = (15.5 \pm 0.5) \text{ MeV}$, $a = \frac{A}{\alpha} \text{ MeV}^{-1}$ with $\alpha = 12 \pm 0.5$

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