Width and Strength of the Hot Giant Dipole Resonance: the Role of the Life Time of the compound nucleus and the Transition from Order to Chaos.

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One of the most surprising discoveries of the past decade is that hot compound nuclei which were thought of as very chaotic systems [1] may exhibit regular collective motions [3]. In particular, looking at the γ decay spectrum one observes ~~A~~ bump in the γ decay spectrum is observed at high energ~~y~~ies which is due to the excitation of the Giant Dipole Resonance (GDR) in the compound → p-33 nucleus. It was shown that this collective state is very "robust" and that it remains nearly unaffected by the increase of excitation energy. It was even proposed that the presence of collective states can be a signature of the existence of a compound nucleus and that the disappearing of the GDR can be interpreted as a signal of the liquid-gas phase transition in nuclei [4]. However, the behavior of the GDR for temperature around 5 MeV is still a matter of controversy.

In particular it has been recently proposed based on the possible existence of pre-equilibrium effects in the γ-ray emission from a hot system [10]. Indeed, if the evaporation time becomes larger than the spreading width of the GDR one might expect that during the time the resonance gets equilibrated the compound nucleus will have cooled down by particle emission. However, we have recently discussed that this idea cannot apply to reactions for which an explicit dipole moment (or strong fluctuation) is present in the entrance channel [13] and so new experimental results looking at the effects of the N/Z entrance channel assymmetry are called for [13].

Since the observed photons are coming from transitions between two states of the compound nucleus which have finite life times, the total width of the photo-absorption peak must contain their individual widths. Since these widths are rapidly increasing with the temperature of the system they will induce a strong brosdening of the GDR photo-absorption peak which may partly explain the rapid suppression of the GDR photons at high excitation energy.

In order to make this point clear it can be useful to discuss the difference between the spreading width and the life time of the compound nucleus. A resonance can be understood as a coherent excitation of particle-hole configuration on a hot nucleus. This is obviously not an eigen state of the compound nucleus therefore it acts as a doorway state and, as the time goes on, it couples with more complicated configurations. Eventually, it will reach a compound nucleus state which is a mixture of many particle-many hole excitations. This "decay" must be understood as the beating of the various compound nucleus states composing the resonance because of their spreading in frequency.

This is not really associated with a life time. In particular for a finite number of compound nucleus states one might observe a Poincare recurrence time where the system is coming back to the initial configuration. Moreover, a life time implies an exponential decrease of the initial population of excited states, consequently it is always associated with a Lorentzian shape of the strength function which is nothing but a Fourier transform of the time evolution. Conversely the shape of the spreading width is not constrained at all.

The only real life time is the one due to the decay of the compound nucleus states through evaporation of particles. This decay induces an exponential decrease of the amplitude associated with each compound nucleus level and a broadening of the corresponding peak in the strength.function.

Since gamma-rays are transitions between two levels of the compound nucleus the broadening will correspond to the sum of the initial and final width. If we now replace the width of the initial and final states by the average evaporation width of the compound nucleus, Γ_{ev}, and if we approximate the shape of the GDR by a gaussien centered at the energy E_{GDR} with a finite width Γ[1] we can demonstrate that the position of the photoabsorption peak is not affected but the width becomes [2]:

$$\Gamma_{GDR} = \sqrt{\Gamma^2 + (2\Gamma_{ev})^2} \tag{1}$$

This result demonstrates that the width of any structure in the photo-absorption spectrum is bigger than $2\Gamma_{ev}$ in perfect agreement with the Heisenberg uncertainty principle. This yields to the conclusion that

$$\Gamma_{GDR} \geq 2\Gamma_{ev} \tag{2}$$

At low excitation energy the life time of the compound nucleus is so long that the influence of this width can be neglected. However at high temperature this life time becomes so small that the induced widths will eventually dominate over the spreading width of the resonance. The life time of a compound nucleus at such temperature is not really known experimentally. However, as far as no anomalous diffusion is appearing at high excitation energy, this life time can be inferred from statistical calculations. Typical results of such calculations are shown in Fig 1 for a ^{120}Sn nucleus. The life time of the compound nucleus rapidly decreases so that Γ_{ev} reaches 10 MeV between 300 and 600 MeV excitation energy depending upon the various level density parameter used in the calculation of the life time. Therefore, the total width of the resonance will show a rapid increase irrespectively of the actual calculations of the spreading width of the resonance. This fact is simply illustrated in Fig. 1 assuming a constant spreading width of 4.4 MeV for the GDR. On the various curves one can see that the width induced by the finite life time of the compound nucleus states dominates above 300 to 500 MeV excitation energy.

This calculation must only be considered as qualitative because of the uncertainties on the estimation of the width of the compound nucleus states. In particular, one may worry about the fact that the introduction of new decay channels such as the emission of intermediate mass fragment will reduce further the life time of the compound nucleus.

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[1] This width represents not only the spreading width but is supposed to be an effective width which includes all the other sources of broadening (deformation, shape fluctuations, ...). These processes being statistical it is normal to assume that the strength function is akin to a normal distribution.

[2] If the various components of the folding product are rather akin to normal distributions than to Lorentzian, the total width becomes the square root of the quadratic sum of the various widths[19]

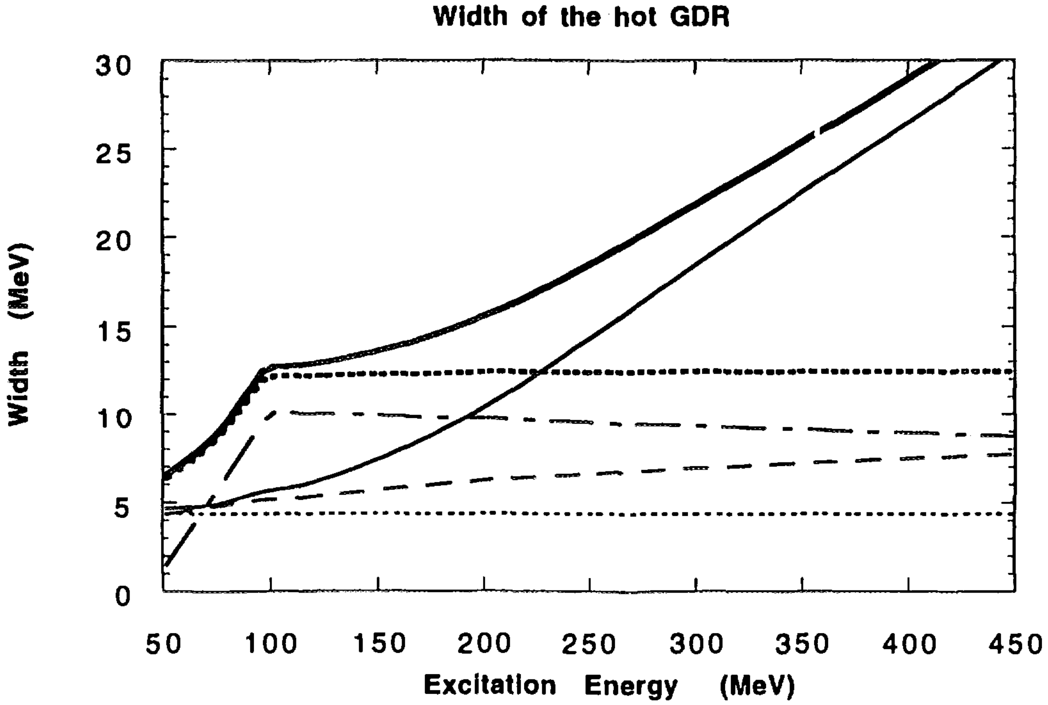

Figure 1. Evolution of the various Widths as a function of the excitation energy of the Sn nucleus, the thick lines represent the width of the GDR, the thin lines the width of the compound nucleus. The solid lines are associated with a level density parameter $a = A/12$, the dash lines with $a = A/10$ and the dash-dotted lines with $a = A/8$.

However this effect will increase the width of the compound nucleus states and so the increase of the GDR width will be faster but the overall picture will not be changed.

The second explanation of the quenching of the GDR strength is related to the fact that each individual particle emission induces a strong fluctuation of the dipole moment of the nucleus. Indeed, if a neutron is emitted the dipole moment will fluctuate with an amplitude

$$\Delta D \approx R/N \approx 0.2 fm \tag{3}$$

where R is the nucleus radius and N its number of neutrons. This value is of the same order of magnitude than the amplitude of one dipole phonon ($\Delta D_1 \approx 4/\sqrt{AmE_{GDR}} \approx 0.2 fm$). Therefore the evaporation of one particle is giving strong kicks to the collective vibration. This classical picture is confirmed by the experimental observation of the particle decay of the GDR. Therefore, the description of the dipole collective variable is akin to the problem of a brownian motion in an harmonic potential. If the time between two evaporations is long in comparison with the period of the vibration, the system will present harmonic dipole oscillation and therefore will be able to emit γ-rays at the dipole frequency. Conversely, when the time between two particle emissions becomes much shorter than the time the system needs to complete one oscillation, the dynamics become stochastic. In such a case the motion is no more characterized by the GDR frequency and the observed γ-spectrum will be flat.

One can conclude that when the time between two particle emissions becomes comparable to the period of the harmonic oscillation, the transition between the order and the

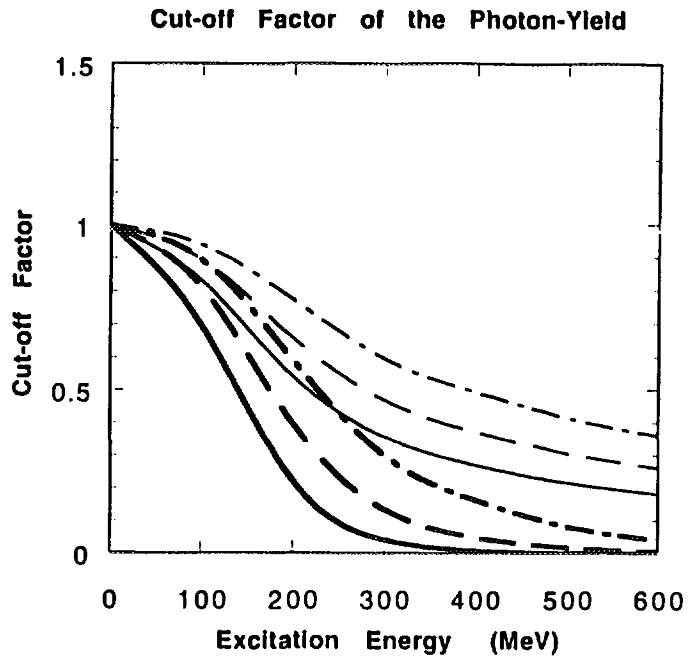

Figure 2. Evolution of the suppression factor as a function of the excitation energy of the Sn nucleus, the thick lines are computed from Eq. (7), the thin lines represent the cut-off factor proposed in ref [10]. The solid lines are associated with a level density parameter $a = A/12$, the dash lines with $a = A/10$ and the dash-dotted lines with $a = A/8$.

chaos is reached and the collective vibration is suppressed (see Fig. 2).

From this simple argument a quenching factor can be deduced and compared with the existing suppression factors. This factor can be easily estimated by computing the number of systems which were able to perform at least one vibration:

$$S(E) = \exp\left(\frac{-2\pi\Gamma_{ev}}{E_{GDR}}\right) \tag{4}$$

This factor is represented on Fig. 2 and compared with the cut-off factor used in fitting the data. One can see that the two are rather similar and so the factor (4) may be a good alternative in order to explain the observed suppression of the γ emitted in heavy ion reactions. Indeed, we demonstrated in reference [13] that the cut-off factor proposed by Bortignon et al was not applicable in the case of reaction with asymmetric N/Z ratio between the target and the projectile. In particular, it is clear that as soon as the incomplete fusion regime is reached this factor which is due to pre-equilibrium effects is not present because of the strong entrance channel fluctuations. However, the suppression seems to be present in the experimental data and can be explained by this transition between regular and stochastic motion. is discussed

In this paper we have discussed the fact that the total width of the γ-ray spectrum of the GDR transitions must contain twice the width of the compound nucleus levels. This implies that one must expect a rapid increase of the width of the GDR. This increase contributes to the observed saturation of the photon multiplicity.

Finally, we proposed A new suppression factor due to the lost of collectivity induced by is proposed.

the fast particle emission This factor is important when the time between two particle emissions (the life time of the compound nucleus) is shorter than the vibration period. This cut-off factor can be a good alternative to the one proposed by Bortignon et al [10] which has been demonstrated to be not applicable in asymmetric N/Z reactions and in incomplete fusion regime where the saturation is observed[13] .

These two effects related to the short life time of the Hot compound Nucleus are important and must be considered in the study of the GDR γ-rays. They may provide a physical interpretation of the observed increase of the GDR width and of the saturation of the photon yield.

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