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COLLECTIVE DOORWAYS AND STATISTICAL DOORWAYS: THE DECAY PROPERTIES OF GIANT MULTIPOLE RESONANCES

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ABSTRACT

A theoretical framework for the description of the decay of giant multipole resonances is developed. It is shown that the statistical decay of the GMR is not necessarily described by the Hauser-Feschbach theory owing to the existence of a mixing parameter. The contribution of pre-equilibrium emission to the GMR decay is also discussed.

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The study of the decay properties of giant multipole resonances (GMR) is of paramount importance for the unraveling of their dynamical, microscopic structure. Since giant resonances are located at high excitation energies, they mainly decay by particle emission. Treated as isolated resonances, the GMR are characterized by a total average width composed of two pieces: the "escape width", $\Gamma^{\uparrow}$, which represents the coupling of the GMR to the continuum, and the spreading width, $\Gamma^{\downarrow}$, that measures the degree of fragmentation of the strength due to coupling to complex intrinsic nuclear configurations (e.g. 2p–2h)[1].

Borrowing from pre-equilibrium reaction theories, one may envisage the following sequence of configurations through which the excited nucleus passes on its way to equilibrium (see Fig. 1). Of course, whereas the first stage of the reaction, namely the giant resonance population, is a very coherent process, in which 1-particle 1-hole configurations act in phase, the other, more complicated stages, are complex enough to call for a statistical treatment.

It has so far been a common practice to analyze the particle spectra originating from the decay of GMR with one of two extreme models, which ignore completely the intermediate, pre-equilibrium stages[1,4]. These models either assume the dominance of $\Gamma_1^{\uparrow}$, namely the GMR decays predominantly "directly", or the predominance of $\Gamma_{H.F.}$, which implies necessarily that the fragmentation of the resonance into the complex background is complete. In this last case the Hauser-Feshbach theory is utilized in the analysis[4]. To give idea about the result of analyses which assume either one of the two limiting models mentioned above, we present in Table 1 a summary of the results, taken from Ref. 5), concerning the percentage contribution of the "direct" decay in several nuclei in different mass regions.

It seems clear to us, though, that a less prejudiced analysis, should involve, at least, the contribution of both the "direct" decay, exemplified by $\Gamma_1^{\uparrow}$, as well as the statistical decay, usually described by the Hauser-Feschbach theory. Unitarity, of course, will indicate the interconnection between the two (or more) contributions.

It is the purpose of this paper to supply a consistent theory of GMR decay into the continuum, which contains the "direct" component, as well as the equilibrated compound nucleus part. We stress that owing to the inevitable unitarity constraints, the compound piece is not necessarily of the Hauser-Feshbach form, particularly if preequilibrium emission is also taken into account.

We first consider the "direct"+compound case. The generalization to include preequilibrium emission is then made next. Our starting point is the observation that because of the clear difference in the time delays associated with the GMR and the compound nucleus resonances, we take the former to constitute a "direct" process. This is to be understood in the sense of the energy variation of the underlying S-matrix: At the level of the fine structure fluctuations attached to the CN resonances, the GMR modulation is locally very smooth.

We introduce now the projection operators P and Q, which are defined such that when operating on the total nuclear wave function, P projects out <u>both</u> the open decay channels and the GMR. Q is simply 1-P. A simplified model for Q would be to consider it as a projector of compound nuclear states. Using the optical background representation of Kawai et al.[6], we may write the energy averaged cross section as a sum of that containing the P channels plus the cross section describing the constitution of the Q-channels, namely

$$\overline{\sigma}_{cc'} = \sigma_{cc'}(P) + \sigma_{cc'}(Q) \tag{1}$$

In the absence of GMR, $\sigma_{cc'}(Q)$ reduces, when no direct channel coupling is present, to the well known Hauser-Feshbach form. Considering the contribution of only one partial wave,

$$\sigma_{cc'}(Q) = \frac{T_c(J)\,T_{c'}(J)}{\sum_{c''} T_{c''}(J)}\,(2J+1)\,\frac{\pi}{k_c^2} \tag{2}$$

In the presence of the GMR, treated as a doorway, $\sigma_{cc'}(Q)$ becomes different from (2) even if direct channel coupling is ignored. To give an example, we consider a photo-nuclear reaction populating, e.g. the giant dipole resonance. Then $T_c(J)$ is just the γ-nuclear formation probability, and $T_{c'}$ may be taken to represent the neutron transmission coefficient. Since neutrons may be emitted directly from the doorway (GMR) as well as from the compound system, $T_{c'}(J)$ must be composed of two pieces[7,8)]

$$T_{c'}(J) = \tau^{C}_{c'}(J) + \mu\,\tau^{D}_{c'}(J) \tag{3}$$

where $\tau^{C}_{c'}(J)$ represents the compound nucleus neutron decay transmission coefficients and $\tau^{D}_{c'}(J)$, the doorway contribution. The factor μ is a mixing parameter which measured the degree of fragmentation of the doorway. It is related to the doorway spreading width $\Gamma_D^{\downarrow}$ by

$$\begin{aligned} \mu &= \Gamma_D^{\downarrow}/\Gamma_D \quad , \\ \Gamma_D &= \Gamma_D^{\downarrow} + \Gamma_D^{\uparrow} \end{aligned} \tag{4}$$

In fact, μ is incident energy-dependent owing to the doorway resonance modulation[9,10)]. However, we are fixing the incident energy to be on resonance.

Clearly the $T_{c''}$ that appears in the denominator of Eq. (2) must have the same structure as in Eq. (3).

At this point it is important to mention that although the transmission coefficient $T_{c'}(J)$ of Eq. (3) contains a term that is explicitly related to the GMR namely $\mu\tau^{D}_{c'}(J)$ (which is by definition shorter-lived than the compound states), the overall time-delay content of it is consistent with that connected with the Q-space. This is so since the mixing parameter, μ, exemplifies a higher order process which necessarily takes longer time to occur than the "direct" process described by $\sigma_{cc'}(P)$, Eq. (1), which we proceed now to discuss.

Because of the mixing of the GMR with the compound nuclear states, it is clear that the term in the cross section that describes the faster, "direct" decay process, $\sigma_{cc'}(P)$, should contain a depletion factor. In fact, the theory of Hussein and McVoy[8], of multistep compound processes, clearly identifies this depletion factor, for the two-step case considered here, to be $(1-\mu)$, with μ given by Eq. (4). Thus, we have for the direct cross section, in the absence of direct $c \to c'$ transition

$$\sigma_{cc'}(P) = (1-\mu)\,\tau^{D}_{\gamma}\,\frac{\tau^{D}_{c'}}{\sum_{c''}\tau^{D}_{c''}} \tag{5}$$

where $\tau^{D}_{c'}$ is given by $4\,\frac{\Gamma^{D}_{c'}}{\Gamma_D}$ [10].

We should stress here that $\sigma_{cc'}(P)$ is <u>not</u> treated statistically as was done in the evaluation of $\sigma_{cc'}(Q)$, Eq. (2), although the Hauser-Feshbach-like form, Eq. (5), may apparently indicate otherwise. The GMR appears in $\sigma_{cc'}(P)$, as usual, in the form of a Lorentzian-shaped isolated resonance. The form given in Eq. (5) is the result obtained when setting the incident

C.M. energy equal to the energy of the GMR, and identifying τ_D^C with $4\Gamma_c^D/\Gamma_D$. (Notice that $\Gamma_D^{\uparrow} = \sum_c \Gamma_c^D$).

We thus have finally for the energy-averaged cross section, $\sigma_{cc'}$, the following (again assuming a γ-induced reaction)

$$\bar{\sigma}_{cc'} = (1-\mu)\tau_\gamma^D \frac{\tau_{c'}^D}{\sum_{c''}\tau_{c''}^D} + \mu\tau_\gamma^D \frac{\tau_{c'}^C + \mu\tau_{c'}^D}{\sum_{c''}\left(\tau_{c''}^C + \mu\tau_{c''}^D\right)} \tag{6}$$

when the factor $(2J+1)\frac{\pi}{k^2}$ is absorbed in τ_γ^D.

In Eq. (6) the γ-absorption is assumed to occur predominantly through the GMR. The factor $\mu\tau_\gamma^D$ that appears in the second term of Eq. (6) contains the mixing parameter μ, owing to the same time-delay argument used in the construction of $T_{c'}(J)$ (see discussion following Eq. (4)).

Eq. (6) is the principal result of this investigation. It clearly exhibits the time-delay difference between the two competing decay processes, through the presence of the fundamental mixing parameter μ. Two important limits can be easily identified. The strong mixing case, $\mu=1$, washes out the doorway nature of the GMR, and accordingly gives

$$\sigma_{cc'}^{SM} = \tau_\gamma^D \frac{\tau_{c'}^D + \tau_{c'}^C}{\sum_{c''}\left(\tau_{c''}^D + \tau_{c''}^C\right)} \tag{7}$$

$\sigma_{cc'}$ above is clearly identified with the usual Hauser-Feshbach result since the decay branching ratio involves $\tau_{c'}^C + \tau_{c'}^D$, a genuine optical transmission coefficient.

The second limiting case in the weak mixing case, $\mu=0$, which yields straightforwardly

$$\sigma^{WM}_{cc'} = \tau^{D}_{\gamma} \frac{\tau^{D}_{c'}}{\sum_{c''} \tau^{D}_{c''}} \tag{8}$$

Clearly no reference is now made to the compound nucleus owing to the doorway nature of the formation process exemplified by the γ-transmission coefficient τ^{D}_{γ}. In the more general case, Eqs. (6), (7) and (8) come out symmetrical in the forms of the entrance and exit channel transmission coefficients[11].

So far, analyses of data, have been performed assuming either Eq. (7) or (8), depending on the part of the spectrum considered. A more consistent approach, however, should start with our Eq. (6) with the aim of extracting the value of μ. This procedure has been followed previously in connection with isospin mixing in nuclear compound reactions, namely the case of analog resonances coupled to the lower-isospin background[12]. The parameter μ extracted in this case measures the degree of nonconservation of isospin due to Coulomb mixing of the upper and lower isospin states.

In the case studied here, μ should measure the degree of GMR fragmentation into the more complex compound nucleus configurations. The unambiguous extraction of μ, however is directly tied to the a priori knowledge of τ^{D}_{c} and τ^{C}_{c}. The former can be calculated using a suitable RPA description of the coherent 1p-1h excitation in the region of high excitation energies[1] (temperature-dependent RPA). The compound transmission coefficient can be evaluated using the optical model. We should stress that the Hauser-Feshbach evaluation of the second term in Eq. (2) is not valid owing to the presence of the unknown parameter μ. If such a calculation were to be performed, one ends up evaluating $\tau^{D} + \mu\tau^{C}$, whose interpretations in terms of optical potentials. is to say the least, ambiguous.

Before ending, we dwell a little on a possible generalization of Eq. (6) to incorporate the contribution arising from pre-equilibrium emission (e.g. from the 2p-2h stage). This is easily accomplished using the nested doorway approach of Ref. 8). The important new features are that the cross section is now composed of three distinct pieces, and the mixing parameter μ is divided into three terms. Namely[11]

$$\overline{\sigma}_{cc'} = \sigma_{cc'}(\mathcal{P}) + (1-\mu_2)\mu_1\tau_\gamma^D \frac{\tau^P_{c'} + \mu_1\tau^D_{c'}}{\sum_{c''}\left(\tau^P_{c''} + \mu_1\tau^D_{c''}\right)} + (\mu_1\mu_2+\mu')\tau_\gamma^D \frac{\tau^C_{c'} + \mu_2\tau^P_{c'} + (\mu_1\mu_2+\mu')\tau^D_{c'}}{\sum_{c''}\left(\tau^C_{c''} + \mu_2\tau^P_{c''} + (\mu_1\mu_2+\mu')\tau^D_{c''}\right)} \tag{9}$$

with

$$\sigma_{cc'}(\mathcal{P}) = (1-\mu_1-\mu')\tau_\gamma^D \frac{\tau^D_{c'}}{\sum_{c''}\tau^D_{c''}}$$

In the above μ_1 measures the mixing of GMR with the 2p-2h states, which can be evaluated using the extended RPA approach of Ref. 13). μ_2 refers to the mixing of the 2p-2h with the compound nuclear states and μ refers to the mixing of the GMR directly with the compound states, which may be set equal to zero for all practical purposes[14]. The transmission coefficient related to the GMR (1p-1h), the preequilibrium stage (2p-2h) and the compound stage are called τ^D, τ^P and τ^C, respectively. It is important to note here that unitarity is preserved both in Eqs. (6) and (9) in the sense that by summing over the final channels c', we obtain

$$\sum_{c'} \overline{\sigma}_{cc'} = \tau_{\gamma}^{D} \tag{10}$$

irrespective of the detailed nature of the decay.

In conclusion, we have developed in this paper, a theoretical framework through which the analysis of GMR decay can be performed in a consistently unitary way. The result of such an analysis, done in conjunction with an RPA (and/or extended RPA) calculation should furnish a measure of the mixing parameter, which is of paramount importance for the understanding of the GMR. Application of the above formalism to data analysis, as well as a more detailed account of the discussion above is under way[10].

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GMR	NUCLEUS	$\Gamma_1^{\uparrow}/\Gamma_{H.F.}$ (%)
E0	^{208}Pb [a], ^{90}Zr [b]	10 - 20
E1	Light Nuclei ($A \geq 40$) [c]	$\sim$ 100
E1	^{209}Bi [d,e], ^{208}Pb [f,g,e] ^{141}Pr [e], ^{89}Y [e]	10 - 20
E2	Light Nuclei ($A \leq 40$) [h]	$\sim$ 100
E2	^{119}Sn [i], ^{208}Pb [j] ^{92}Zr [k]	$\sim$ 10 - 20

Table 1 - **Tabulation of percentage contribution of "direct" decay** ($\Gamma_1^{\uparrow}/\Gamma_{H.F.}$) of the E0, E1 and E2 giant **resonances for various nuclei, collected from Ref. 5).**

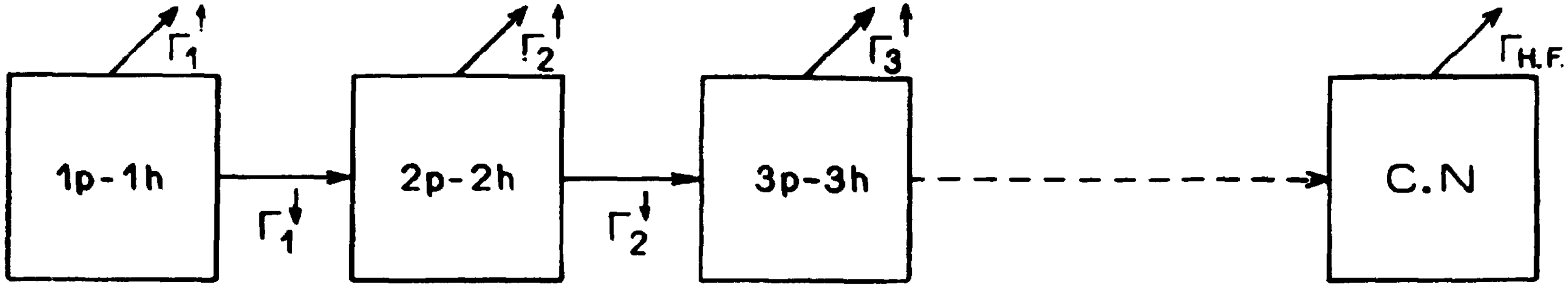

FIGURE CAPTIONS

Figure 1 - A schematic diagram showing the sequence of events that may occur in the formation of the compound nucleus via the giant resonance.