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GIANT RESONANCES: REACTION THEORY APPROACH*

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Side by side with the powerful entropy source in the short–distance/high–energy domain of nuclear physics, which has been generating conspicuous collective flows of interest within the nuclear physics community, sophistication of experimental techniques and facilities have been providing for new sources of heat also in the better known and yet not sufficiently understood larger–distance/lower–energy domain. In particular, the possibility of performing detailed exclusive measurements of cross–sections to the many available decay channels following excitation of Giant Multipole Resonances (GMR)[1–4] led one to view these phenomena as complicated dynamical syndromes so that theoretical requirements for their study must be extended well beyond the traditional bounds of nuclear structure models. In fact, the realization that e.g. the spectra of decay products following GMR excitation in heavy nuclei are well described by statistical model (Hauser–Feshbach, HF) predictions[5] indicated that spreading of the colletive modes plays a major role in shaping exclusive cross–sections (see fig.1). The evaluation of these, therefore, necessarily involves all the meanders of a comprehensive nuclear–reaction theoretical framework implemented so as to shelter also the available inputs from existing nuclear structure studies. Alternatively, the GMR syndrome has been approached from the point of view of kinetic theory[6], which relates spreading to dispersion and collisional damping[6,7]. Given the necessary limitations of a short presentation, however, this interesting developement, which can be naturally extended to GMR in excited ("hot") nuclei[8], will not be considered here any further.

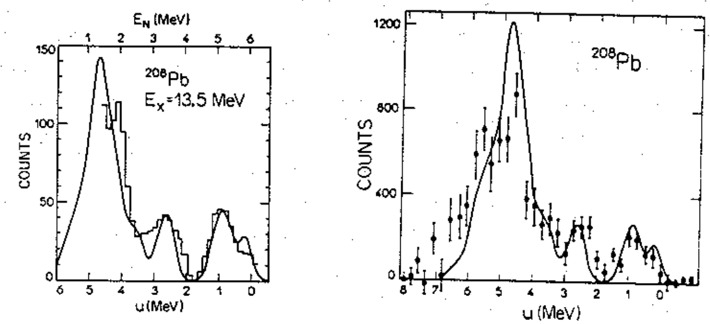

Fig. 1 – HF fits to neutron spectra from the decay of the EO GMR in ^{208}Pb. From refs. (5).

Regarding the reaction theory approach, the situation one finds in conection with the GMR is not new, as it reproduces that which has been studied two decades ago in conection with the excitation of Isobaric Analog Resonances (or Giant Fermi charge–exchange Resonances)[9,10]. A pioneering implementation of this comprehensive approach in the case of the GMR haas been carried out by Dias, Hussein and Adhikari[11], who proposed a paradigm for the analysis of exclusive data[12]. This is based on the expression[11]

$$<\sigma^c> \propto (1-\mu)\, \tau_D^{in} \frac{\tau_D^c}{\sum_{c'} \tau_D^{c'}} + \mu\, \tau_D^{in} \frac{\tau_Q^c + \mu\ \tau_D^c}{\sum_{c'}(\tau_Q^{c'} + \mu\tau_D^{c'})} \qquad (1)$$

in which the energy–averaged cross–section to channel c is written in terms of compound nucleus and GMR doorway transmission coefficients, τ_Q^c and $\tau_D^c \sim 2\pi\Gamma^c\rho_D$, and a mixing parameter $\mu \sim \Gamma^{\downarrow}/\Gamma$. The quantities Γ^c, $\Gamma^{\downarrow}$ and Γ stand for the doorway partial decay width to channel c, spreading width and total width respectively. The first term of eq.(1) represents the semi–direct process in which the produced doorway decays through channel c, while the second term is the fluctuation cross–section. The interconnection of the two terms via the mixing parameter accounts for unitarity. The success of HF predictions implies that fits to data lead to values of μ close to 1[11–13], in association with rather small doorway transmission coefficients. In applications of eq.(1) the experimental cross–sections were actually integrated over an energy interval of the order of the width of the doorway bump[12], or at least use generous slices of excitation energy range[11]. However, it has also been noted by Dias et al.[11] that the mixing effects are in general energy–dependent, reflecting the doorway resonance modulation. Since in the case of the GMR this can be as much as a few MeV wide, such energy dependence should be considered as a potentially useful element in the analysis, especially in connection with good resolution electro– or photoexcitation data. It is therefore of interest to see what it is predicted to be by a more detailed theory.

The situation one may wish to consider involves direct inelastic scattering of a projectile (electron, or light or heavy ion) in association with the production, possibly "inter alia", of GMR's in the target system (see fig.2). The relevant

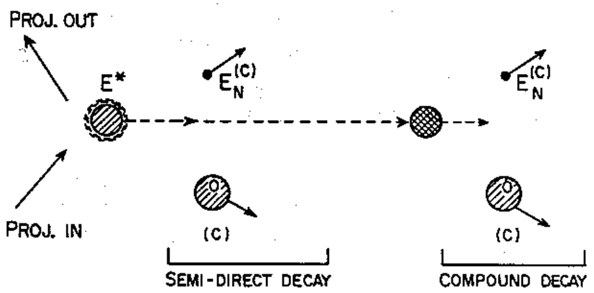

Fig. 2

quantities to study are then energy averaged cross–sections to definite final channels c for given target excitation energy, i.e., the energy differential cross–sections $<d\sigma^c/dE^*>$. A derivation is out of place here and is actually available e.g. in ref[9]. What one gets by working out the casse of an isolated doorway (GMR) is an expression having just the structure of eq.(1), namely

$$\left\langle \frac{d\sigma^c}{dE^*} \right\rangle \propto \tau_D^{in} \frac{d\mu}{dE^*} \frac{\Gamma^c}{\Gamma^{\downarrow}} + \tau_D^{in} \frac{d\mu}{dE^*} \frac{\tau_Q^c + \Gamma^c \frac{d\mu}{dE^*}}{\sum_{c'} \tau_Q^{c'} + \Gamma^{\uparrow} \frac{d\mu}{dE^*}} \tag{2}$$

where $\Gamma^{\uparrow} = \sum_c \Gamma^c$. Here, however, the doorway resonance modulation appears explicity through the energy–differential mixing parameter

$$\frac{d\mu}{dE^*} = \frac{1}{2\pi} \frac{\Gamma^{\downarrow}}{(E^* - E_D)^2 + \frac{\Gamma^2}{4}} . \tag{3}$$

As a point of both qualitative and quantitative importance note that $\Gamma^c\, d\mu/dE^*$ now replaces the doorway contribution $\mu 2\pi \Gamma^c \rho_D$ to the fluctuation cross–section branching factor appearing in eq.(1). The quantity $d\mu/dE^*$ represents in fact the only meaningful doorwaay density in the isolated doorway situation. Quantitatively, the doorway effects in the branching ratios are thereby reduced, even on resonance, by about one order of magnitude compared to what one would get using eq.(1) with $\rho_D \sim 1\ MeV^{-1}$ [11–12]. In fact, on resonance one has

$$\left.\frac{d\mu}{dE^*}\right|_{E^*=E_D} = \frac{2}{\pi} \frac{\Gamma^{\downarrow}}{\Gamma^2} \sim \frac{2}{\pi\Gamma} \quad \text{or} \quad \rho_D = \frac{1}{\pi^2 \Gamma} .$$

Some comments on the general ingredients and assumptions involved in the derivation of eq.(2) are appropriate here. The derivation is based on a decomposition of the phase space of the target system in three mutually coupled subspaces (see fig.3), namely the doorway subspace, the compound subspace and the subspace of open decay channels. The production (inelastic scattering) stage is assumed to feed only the doorway subspace. In fact, direct (e.g. knock out) transitions from the production stage to the decay channels are possible and have actually been invoked to interpret asymmetries observed in the angular distributions of the decay products following excitation of isoscalar resonances in ^{24}Mg and ^{40}Ca by inelastic α–scattering[1]. These direct transitions are associated with additional amplitudes that will interfere with the semi–direct

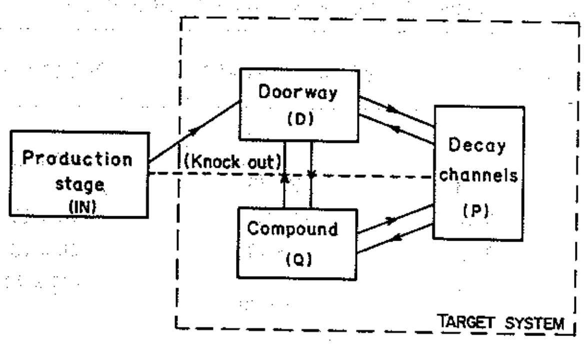

Fig. 3

process. They are being left out of the present discussion for simplicity, since no fingerprints of them seem to have been detected in cases studied so far involving heavier targets.

There are at least two different strategies that one may adopt for setting up the doorway subspace D. First, one can collect in D the normalized states which result from the application to the target ground state $|0\rangle$ of appropriate multipole excitation operators, $F_{J^\pi T}|0\rangle$, in the spirit of the "sum–rule approach" to the discussion of GMR phenomena[13]. The $F_{J^\pi T}$ are one–body multipole operators whose particular form depends on the production mechanism and which have been studied in great detail e.g. for inelastic electron scattering[14]. Since they are not constants of motion, the resulting doorway states will be spread over the actual energy eigenstates of the target system. This spreading is described through their coupling to the remaining two subspaces. The channel subspace P is characterized in terms of the relevant asymptotic residual states (orthogonalized to D), while the compound subspace is just the complement of P plus D. In this way, one–body excitations of the target ground state having zero multipole strength are included in P or in Q, so that the so called "Landau damping"[15] of the GMR doorways appears as part of the spreading width in this case.

An alternate strategy for the analysis of the phase space of the target system consists in letting P+D include arbitrary one–body excitations of the target ground state, in addition to relevant channels with a different structure. The projected effective dynamics within this doorways plus open channels subspace generates an extended Random Phase Approximation out of which one can obtain, by futher projecting out the asymptotically free fragments, a discrete set of complex, normalized states that will act as multipole doorways[16]. It is important to stress that the particle–hole coupling to be diagonalized here includes processes which go via the virtual excitation of compound modes, i.e., the so called induced interaction effects. To state a connection between the two strategies, one may remark that the excitation operator doorways can be expanded into the set of complex dynamical doorways of the second approach. In the latter case the D+P subspace is actually larger than in the first case, and includes the zero–strength one–body modes responsible for the Landau damping. In order to avoid as much as possible dealing explicitly with the nuclear dynamics involved in the second strategy, and having in mind the goal of describing cross–sections averaged over the fine structure of GMR, excitation operator doorways will be implied in the rest of the present discussion. The restriction to a single, isolated doorway can then be naturally associated with the identification of a definite excitation mechanism and multipolarity. In the case of inelastic hadron scattering this includes, in particular, the ability to experimentally distinguish between "peak" and "background" yields.

In order to have an expression for the exclusive cross–section integrated over the doorway bump, $\langle\sigma^c\rangle$, one may replace energy–dependent transmission coefficients and widths by constant average values and then integrate over the resulting combination of Breit–Wigner line shapes to obtain

$$\langle\sigma^c\rangle \propto \tau_D^{in}\frac{\Gamma^c}{\Gamma} + \tau_D^{in}\frac{\Gamma^\downarrow}{\Gamma}\left[\frac{\tau_Q^c}{\sum_{c'}\tau_Q^{c'}}\frac{1}{\sqrt{1+\Delta}} + \frac{\Gamma^c}{\Gamma^\uparrow}\left[1-\frac{1}{\sqrt{1+\Delta}}\right]\right] \qquad (4)$$

with

$$\Delta = \frac{1}{\sum_{c'}\tau_Q^{c'}}\,\frac{2}{\pi}\,\frac{\Gamma^\uparrow\Gamma^\downarrow}{\Gamma^2} = \frac{1}{\sum_{c'}\tau_Q^{c'}}\,\Gamma^\uparrow\left.\frac{d\mu}{dE^*}\right|_{E^*=E_D} . \qquad (5)$$

Since the HF denominator is often large compared to unity, Δ is often small, in which case one may profitably expand eq.(4) in powers of Δ. To lowest order the cross–section branching ratios are given by

$$\frac{<\sigma^{c}>}{\sum_{c'} <\sigma^{c'}>} = \frac{\Gamma^{c}}{\Gamma^{\uparrow}+\Gamma^{\downarrow}} + \frac{\Gamma^{\downarrow}}{\Gamma^{\uparrow}+\Gamma^{\downarrow}} \frac{\tau_Q^{c}}{\sum_{c'} \tau_Q^{c'}} + \mathcal{O}(\Delta) \quad . \tag{6}$$

The dominant doorway effects are then seen to be those associated with the semi–direct process. As for the energy–differential branching ratios, eq.(2) gives

$$\frac{\left\langle \frac{d\sigma^{c}}{dE^{*}} \right\rangle}{\sum_{c'} \left\langle \frac{d\sigma^{c'}}{dE^{*}} \right\rangle} = \frac{1}{1 + \frac{1}{\sum_{c'} \tau_Q^{c'}} \Gamma^{\uparrow} \frac{d\mu}{dE^{*}}} \left[\frac{\Gamma^{c}}{\Gamma^{\uparrow}+\Gamma^{\downarrow}} + \frac{\Gamma^{\downarrow}}{\Gamma^{\uparrow}+\Gamma^{\downarrow}} \frac{\tau_Q^{c}}{\sum_{c'} \tau_Q^{c'}} + \right.$$

$$\left. + \frac{1}{\sum_{c'} \tau_Q^{c'}} \Gamma^{c} \frac{d\mu}{dE^{*}} \right] \tag{7}$$

which shows that to order zero in Δ the doorway resonance modulation entering through $d\mu/dE^{*}$ disappears.

Recently S. Brandenburg et al.[17] have performed a re–analysis of their $^{208}Pb(\alpha,\alpha'n)$ data in which measured peak integrated branching ratios are used to deduce widths Γ^{c} corresponding to the semi–direct decay of the Isoscalar Giant Monopole Resonance. This analysis can be understood as involving the use of eq.(6) with the approximation $\Gamma^{\downarrow}/\Gamma^{\uparrow}+\Gamma^{\downarrow} \approx 1$ (in view of the relative smallness of the semi–direct component) and using $\Gamma^{\uparrow}+\Gamma^{\downarrow} \approx 2.5$ MeV. On the other hand, Bracco et al.[3,12] analysed $^{208}Pb(^{17}O,^{17}O'n)$ data using eq.(1) in the excitation energy range corresponding to the same GMR with a similar purpose. The results of the two analyses, quoted in Table 1, show some discrepancies which would in fact be somewhat agravated by the reduction of ρ_D, in the case of the Bracco data, from the adopted value of 1 MeV^{-1}. The reduction would essentially bring the widths deduced by Bracco et al. in line with the use of eq.(2)

Table 1 – Deduced Γ^{c} for the isoscalar 0^{+} GR in ^{208}Pb

Final state	E_{res} (MeV)	Γ^{c} (Ref. 17)(KeV)	Γ^{c} (Ref. 17)(KeV)
$1/2^{-}$	0		} 140 ± 35
$13/2^{+}$	1.63	75 ± 35	
$5/2^{-}$	0.57	< 35	70 ± 15
$3/2^{-}$	0.89	75 ± 40	50 ± 10
$7/2^{-}$	2.34	} 140 ± 30	165 ± 40
$5/2^{+}+7/2^{+}$	2.6		

or, more appropriately, of its integrated form, eq.(6). Discrepancies also occur between the deduced widths and theoretical estimates of the channel widths obtained from continuum RPA calculations reported in ref. 12]. While estimates based on the operator–doorway point of view are clearly desirable, it should also be pointed out that there is also ample room for refinement of the experimental situation. In particular, the handling of the background separation problem differs markedly in the two experiments.

The information on the mean semi–direct decay of the doorway bump as pursued e.g. in these two analyses might in principle be considerably refined if one could measure energy–differential branching ratios accross the relevant energy interval. In fact, by using eq.(7) instead of its integrated form, eq. (6), one could then check the smoothness of the energy–dependence of the semi–direct widths Γ^{c} accross the doorway bump. The occurence of fluctuations of the partial decay widths in the relevant energy interval would signal the presence of further doorway structure, which could in particular be associated with the decay channels themselves, rather than with the production mechanism. Since any further doorway structure of this type involves finer aspects of the many–body dynamics, and in view of the large theoretical uncertainties in this domain[12], it appears at present that this question should be dealt with experimentally. As an ilustration of this, table 2 reports on preliminary results of an analysis along these lines of the Illinois $^{208}Pb(\gamma,n)$ data using tagged photons[4]. Here the most severe limitation comes from the relatively poor

Table 2 – Semi–direct widths deduced at different E^* for $^{208}Pd(\gamma,n)$

		Γ^c (KeV)		
Final state	E_{res}(MeV)	E^*=12.006 MeV	E^*=12.821 MeV	E^*=14.011 MeV
$1/2^-$	0.0	(–55 ± 25)	(–70 ± 15)	55 ± 20
$5/2^-$	0.569	135 ± 40	250 ± 35	160 ± 35
$3/2^-$	0.897	185 ± 45	30 ± 35	70 ± 30
$13/2^-$	1.633	240 ± 30	145 ± 30	115 ± 15
$7/2^-$	2.340	230 ± 35	215 ± 35	155 ± 20

neutron–energy resolution, which gives rise to large uncertainties in the branching ratios to the lowest lying residual states in ^{208}Pb. Consequently, one is not yet able to attribute definite reality to the obtained energy dependence of the extracted partial widths.

In summary, existing tools of reaction theory allow one to derive an explicit form (eq.(3)) for the energy dependence of mixing effects in the production and decay of GMR in the isolated doorway limit. The result indicates that mixing has little effect on branching ratios for the statistical decay, so that the main effect of semi–direct decay is the semi–direct contribution to the cross–section. Energy differential branching ratios may expose further doorway structure, as associated e.g. with decay channel doorways contributing to the spreading of the GMR. Finally, exclusive energy–differential branching ratios measured with enough resolution to separate several individual final channels could be extremely valuable to pin down many detailed properties of the many–body dynamics involved in the spreading of the GMR.

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