PHYSICAL REVIEW C VOLUME 50, NUMBER 6 DECEMBER 1994

Decay properties of giant multipole resonances: Hybrid model for channel types competition

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(Received 26 May 1994)

The decay properties of giant multipole resonances (GMR) are studied using the hybrid model in the context of channel type competition. We found that the analysis of GMR decay with several open channel types has the same analytical expression as when only one channel type is allowed. The generalization of the hybrid model presented provides a simple way to study the competition between the direct and statistical decay of GMR.

PACS number(s): 24.30.Cz, 24.10.Eq, 24.60.Dr

The study of the decay properties of giant multipole resonances (GMR) is of paramount importance for the unraveling of their dynamical and microscopic structure. Since giant resonances are located at high excitation energies, they decay mainly by particle emission. Treated as isolated resonances, the GMR are characterized by a width composed of two pieces: the "escape width" $\Gamma^{\uparrow}$, which represents the coupling of the GMR to the continuum, and the "spreading width" $\Gamma^{\downarrow}$, which measures the degree of fragmentation of the strength due to coupling to complex intrinsic nuclear configurations (e.g., two-particle–two-hole) [1]. Of course, whereas the first stage of the reaction, namely the giant resonance population, is a very coherent process in which one-particle–one-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, preequilibrium stages [2–5]. These models either assume the dominance of $\Gamma^{\uparrow}$, meaning the GMR predominantly decays "directly," or the predominance of $\Gamma^{\downarrow}$, which implies necessarily that the fragmentation of the resonance into the complex background is complete [3,4]. In this last case the Hauser-Feshbach theory [6] is utilized in the analysis.

Within the hybrid model theory [7] the GMR decay by particle emission accounts both for the direct component and for the equilibrated compound nucleus part. This theory was used only in the analysis of exclusive data of the giant monopole ($E0$) resonance in ^{208}Pb [7,8]. This analysis is based on the expression

$$b_i=(1-\mu)\frac{\tau_{iD}}{\Sigma_j\tau_{jD}}+\mu\,\frac{\tau_{ic}+\mu\tau_{iD}}{\Sigma_j(\tau_{jc}+\mu\tau_{jD})}\,, \qquad (1)$$

where b_i is the branching ratio for particle emission to the ith level of the residual nucleus, which is written in terms of the compound nucleus and GMR doorway transmission coefficients, τ_{ic} and $\tau_{iD}\sim 2\pi\Gamma_i^D\rho_D$, and a mixing parameter $\mu=\Gamma^{\downarrow}/\Gamma$ measuring the degree of fragmentation of the doorway. The quantities Γ_i^D and ρ_D are the partial escape width and 1p-1h density states, respectively.

In the application of the above theory for $E0$ decay in ^{208}Pb [7] the meaning of the mixing parameter μ is completely connected with the statistical component of the neutron channels since only these channels are open. In situations where more than one type of channel is open the connection of μ with the statistical component of each channel is not possible since the μ in Eq. (1) is necessarily the same for all types of channels. Also the analysis of experimental data when more than one type of channel is present is complicated because we need information on all types of channels at the same time.

The objective of the present Rapid Communication is to develop a generalization of the hybrid model that accounts for the separation and independence of the particle channels types. In this hybrid model generalization the μ parameter is composed of the various μ_k's belonging to each open channel type, where the μ_k provides the statistical component in the respective branching.

In order to start our formalism we note that, if various channel types are present in the decay, Eq. (1) is written as

$$b_i^k=(1-\mu)\frac{\tau_{iD}^k}{\Sigma_l\Sigma_j\tau_{jD}^l}+\mu\,\frac{\tau_{ic}^k+\mu\tau_{iD}^k}{\Sigma_l\Sigma_j(\tau_{jc}^l+\mu\tau_{jD}^l)}\,, \qquad (2)$$

where k is a running index over the different channel types ($k=\pi$ for protons, $k=\nu$ for neutrons, ...), and the sum in l means that the denominators in Eq. (2) are summed over all particle channels. In Eq. (2), we have

$$\sum_k\left(\sum_i b_i^k\right)=\sum_k P_k=1, \qquad (3)$$

with $P_k=\Sigma_i b_i^k$ defined as the emission probability of the kth particle (obtained from the experimental data).

Then we introduce in Eq. (2) the P_D^k and P_c^k probabilities as follows:

$$b_i^k=(1-\mu)P_D^k\frac{\tau_{iD}^k}{\Sigma_j\tau_{jD}^k}+\mu P_c^k\frac{\tau_{ic}^k+\mu\tau_{iD}^k}{\Sigma_j(\tau_{jD}^k+\mu\tau_{jD}^k)}\,, \qquad (4)$$

with the definitions

$$P_D^k=\frac{\Sigma_j \tau_{jD}^k}{\Sigma_l(\Sigma_j \tau_{jD}^l)} \Rightarrow \sum_k P_D^k=1 \tag{5}$$

and

$$P_c^k=\frac{\Sigma_j(\tau_{jc}^k+\mu\tau_{jD}^k)}{\Sigma_l[\Sigma_j(\tau_{jc}^l+\mu\tau_{jD}^l)]} \Rightarrow \sum_k P_c^k=1 \tag{6}$$

(P_D^k and P_c^k are the direct and compound branching to the k channel type).

From the definitions given above, the P_k probability in Eq. (3) can be obtained by performing a sum over the i index in the b_i^k's of Eq. (4):

$$P_k=\sum_i b_i^k=(1-\mu)P_D^k+\mu P_c^k, \tag{7}$$

with the normalization $\Sigma_k P_k=1$. Since the μ parameter contains information about all channel types, we need to rewrite each piece of Eq. (7) in such a way that P_k contains only information on the respective k channel. Then we start by the recognition of the direct portion $(1-\mu)P_D^k$ in Eq. (7).

If we consider only situations where the GMR may be treated as a single doorway we can write the escape width as a sum of the partial width of the k's particles:

$$\Gamma^\uparrow=\sum_k \Gamma_k^\uparrow, \tag{8}$$

and since the τ_{iD}^k is directly connected with the partial escape width, we have P_D^k written as a ratio of the partial and total escape widths by Eqs. (5) and (8):

$$P_D^k=\frac{\Gamma_k^\uparrow}{\Gamma^\uparrow}. \tag{9}$$

Assuming that $\Gamma=\Gamma^\uparrow+\Gamma^\downarrow$ and observing that $\mu=\Gamma^\downarrow/\Gamma$ we may rewrite it as

$$\mu=1-\frac{\Gamma^\uparrow}{\Gamma}. \tag{10}$$

These equations permit us to separate the direct portion in Eq. (7) for each k channel by the substitution of Eqs. (9) and (10) in $(1-\mu)P_D^k$ as follows:

$$(1-\mu)P_D^k=\frac{\Gamma_k^\uparrow}{\Gamma}=(1-\mu_k)P_k, \tag{11}$$

where μ_k is defined as

$$\mu_k=1-\frac{1}{P_k}\frac{\Gamma_k^\uparrow}{\Gamma}, \tag{12}$$

which is a parameter analogous to the μ of Eq. (2) and measures the statistical component in the decay through the kth particle channel.

The statistical component of P_k [μP_c^k in Eq. (7)] can be rewritten using Eq. (11) as

$$\mu P_c^k=\mu_k P_k, \tag{13}$$

which contains only terms in the kth channel.

With the definitions in Eqs. (11) and (13) the branching ratios in Eq. (4) become

$$b_i^k=(1-\mu_k)P_k\frac{\tau_{iD}^k}{\Sigma_j\tau_{jD}^k}+\mu_k P_k\frac{\tau_{ic}^k+\mu\tau_{iD}^k}{\Sigma_j(\tau_{jc}^k+\mu\tau_{jD}^k)}. \tag{14}$$

In this equation, the competition between direct and statistical decay in systems where different particles may be emitted is clearer than in the analysis by Eq. (2). However, some information on the interference between the channel types still remains in the μ parameter of the second term in the right-hand side of Eq. (14). At this point let us call this term S_{ic}^k:

$$S_{ic}^k=\mu_k P_k\frac{\tau_{ic}^k+\mu\tau_{iD}^k}{\Sigma_j(\tau_{jc}^k+\mu\tau_{jD}^k)}. \tag{15}$$

Utilizing $\Sigma_k P_c^k=1$, as defined in Eq. (6), we obtain the μ parameter by performing a sum in k in Eq. (13) which is composed of all channel types:

$$\mu=\sum_k \mu_k P_k. \tag{16}$$

Now if we introduce the μ expression [Eq. (16)] in Eq. (15) we obtain

$$S_{ic}^k=\mu_k P_k\left\{\frac{(\tau_{ic}^k+\mu_k P_k\tau_{iD}^k)+\Sigma_{l\neq k}\mu_l P_l\tau_{iD}^k}{\Sigma_j[(\tau_{jc}^k+\mu_k P_k\tau_{jD}^k)+\Sigma_{l\neq k}\mu_l P_l\tau_{jD}^k]}\right\}. \tag{17}$$

The interference terms are apparent in Eq. (17) and are contained in $\Sigma_{l\neq k}\mu_l P_l\tau_{iD}^k$ of S_{ic}^k. In cases where the statistical decay dominates and there is a predominance of one channel type (as in a medium mass nucleus), the interference terms may be disregarded in comparison with the other terms, allowing the approximation

$$S_{ic}^k\approx\mu_k P_k\frac{\tau_{ic}^k+\mu_k P_k\tau_{iD}^k}{\Sigma_j(\tau_{jc}^k+\mu_k P_k\tau_{jD}^k)}. \tag{18}$$

This approximation allows the complete separation of the channels types, permitting the analysis of the decay spectra of each particle kind with independent treatment between the channel types:

$$b_i^k\approx(1-\mu_k)P_k\frac{\tau_{iD}^k}{\Sigma_j\tau_{jD}^k}+\mu_k P_k\frac{\tau_{ic}^k+\mu_k P_k\tau_{iD}^k}{\Sigma_j(\tau_{jc}^k+\mu_k P_k\tau_{jD}^k)}. \tag{19}$$

The comparison between the above expression and the experimental data provides an estimation of the μ_k parameter which measures directly the statistical component of the respective channel type. With the analysis of the spectra of all possible particles we can obtain the μ parameter from Eq. (16) and the partial or total escape width in Eqs. (12) and (8), respectively.

Within this approximation the unitarity of the b_i^k [Eq. (19)] is lost in the sense of the hybrid model [Eq. (14)] because we are disregarding the interference terms. But the unitarity is recovered in this approximation when we write the S_{ic}^k in Eq. (18) to contain only terms which correspond to the specific channel type. The unitarity of Eq. (19) of our approximation is equivalent to disregarding τ_{iD} in the statistical component of the hybrid model formalism [see Eq. (1)], which is similar to that of Brandenburg *et al.* [9] and Piza *et al.* [10].

The generalization of the hybrid model proposed here shows that the studies of the GMR decay with channel type competition have the same form as that performed when only one channel type is open and shows that each spectrum is analyzed independently, having its own μ_k. This approximation provides a simple way to study the competition between direct and statistical decay when different kinds of particles may be emitted in the process.

We would like to thank W. A. Seale and M. N. Martins for a critical reading of this manuscript. This work was supported in part by Conselho Nacional de Desenvolvimento Cientifico e Tecnologico (CNPq) and Coordenação de Aperfeiçoamento de Pessoal do Ensino Superior (CAPES).

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