Preequilibrium proton decay in ^{40}Ca

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The proton spectra of the giant quadrupole resonance decay in ^{40}Ca is analyzed. The decay mechanism of this excitation is studied by the inclusion of the semidirect, preequilibrium, and statistical modes through the chaining evolution of the particle-hole configurations. Strong evidence for the contribution of preequilibrium decay of the giant resonance is established.
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I. INTRODUCTION

The excitation and decay of giant resonances (GR's) has been a topic of great interest in nuclear physics research for several years [1–3]. Since the giant dipole resonance was first observed, experimental and theoretical advances led to the observation of new GR vibrational modes and to the development of new structure and reactions mechanisms models. The microscopic structure, based on the collective small-amplitude nuclear response, is mainly built on random phase approximation (RPA) models [4] involving one-particle–one-hole ($1p$-$1h$) states with $2p$-$2h$ ground-state correlations or on other microscopic sophistications such as a second RPA [5] that includes $1p$-$1h$ and $2p$-$2h$ excitations in the creation operators of excited nuclear states, or still in an extended second RPA [6] which improves the second RPA including the $2p$-$2h$ ground state correlations in perturbation theory. As more complicated excitations in the chaining np-nh are introduced to treat the GR spreading, more technical and numerical difficulties, e.g., the large space and continuum effects, arise and the calculations become prohibitive [7]. Nevertheless, approximations [8,9], which include continuum effects in the RPA model, have a simple application for the escape amplitude estimates in GR or still in the valuation of the spreading widths through the inclusion of core excitations, as in a core-coupling RPA [10], to avoid the $2p$-$2h$ technical difficulties caused by a very large space. In the context of GR's decay modes the idea of compound nucleus (CN) formation through the evolution of the chaining np-nh [11,12], where the GR is regarded as the first $1p$-$1h$ doorway, can yield information about the microscopic structure. The escape and/or spreading effects in each evolution stage may be evaluated by the analysis of the measured emitted-particle spectrum [13–16]. Recently, with the new facilities in nuclear physics experiments the double giant resonances [17,18], excited by the first step in GR, are the new objects of study in this theme and the characterization of the GR as excitations with small amplitudes and collectivity is being reviewed and nonlinear effects [17], believed to be important to explain this nuclear excitation mode, are being assessed. In this paper the decay modes of GR are revised with the application and generalization of the previous models [14,12,19] which accommodates the statistical, escape, and spreading effects in the evolution of the np-nh excitations. In Sec. II the formalism employed to the decay modes is discussed. Section III presents the analysis of the proton spectra resulting from the giant quadrupole resonance (GQR) decay in ^{40}Ca and in Sec. IV the conclusions are given.

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II. PREEQUILIBRIUM DECAY

In the hybrid preequilibrium decay formalism one incorporates the GR [12], to reflect collective nuclear effects, into the multistep compound emission (MSCE) theory of Feshbach, Kerman, and Koonin (FKK) [11]. According to this theory Hilbert space is divided into open and closed channels with orthogonal and complementary projectors P (open) and Q (closed) breaking the multistep process into two differents types: the multistep direct reactions described by $P\Psi$ and the multistep compound reactions described by $Q\Psi$, where Ψ is the total wave function. Since the GR is the first stage of the evolution, feeding the increase of np-nh excitations, one can rewrite P space in a way to include the GR, i.e., $P=P'+D$, where D treats the isolated doorway GR as an effective open channel (the entrance channel) and P' arranges the multistep continuum effects in any evolution stage. The Q space contains the multistep compound stages in the various pieces of the evolution and couples the GR to the CN via np-nh ($n>1$). This Hilbert space subdivision reads

$$P=\sum_i P_i+D=P'+D, \quad Q=\sum_j Q_j. \tag{1}$$

The evolution stages ($n=1,2,\ldots,N$) are arranged in doorway classes of successive decreasing average widths Γ_n according to their time delay ($\Delta t_n=\hbar/\Gamma_n$ with $n=1$ in the GR to $n=N$ in the CN), defined as a ‘‘well-nested’’ sequence [20] where the mixing parameters between two successive stages are defined as

$$\mu_{nm}=\frac{\Gamma^{\downarrow}_{nm}}{\Gamma_n}, \tag{2}$$

where $\Gamma^{\downarrow}_{nm}=2\pi[|\langle n|V|m\rangle|^2]/D_m$ is the downward mixing among classes, measured by the coupling of the classes of states through an effective two-body interaction (V), D_m is the level spacing, and Γ_n is given by

$$\Gamma_n=\Gamma^{\uparrow}_n+\sum_{m=n+1}^{N}\Gamma^{\downarrow}_{nm}, \tag{3}$$

where $\Gamma^{\uparrow}_n$ is the escape to the nth stage. If only semidirect and compound nuclei are taken into account, the μ_{nm} becomes the mixing parameter μ of Ref. [14], which gives the coupling between the GR and CN, measuring the trapped flux to the GR spreading. Thus, the Hauser-Feshbach formalism can be generalized including the GR and CN decay with transmission coefficients $T_{c'}$ to a final channel c', given by

$$T_{c'}=\tau^{C}_{c'}+\mu\tau^{D}_{c'}; \tag{4}$$

the superscripts C and D in the τ transmission coefficients refer to CN and GR stages, respectively. Thus, the energy-average cross section in a γ-induced reaction from an entrance channel c to an open channel c' reads [14] like

$$\overline{\sigma}_{cc'}=(1-\mu)\tau^{D}_{c}\frac{\tau^{D}_{c'}}{\sum_{c''}\tau^{D}_{c''}}+\mu\tau^{D}_{c}\frac{\tau^{C}_{c'}+\mu\tau^{D}_{c'}}{\sum_{c''}(\tau^{C}_{c''}+\mu\tau^{D}_{c''})}, \tag{5}$$

where the factor $(1-\mu)$ gives the escape portion of the GR to the continuum and μ the spreading to the CN. The term $\mu\tau^{D}_{c'}$ in the second member gives the feedback to c' through the return of the CN to GR stage. It is worth at this point to note that the sum index c'' in the denominators runs over all channels of different particle types involved in the decay process and the assumption of channel particle-type independence [19] gets the same form for the $\overline{\sigma}_{cc'}$ as in Eq. (5) if we restrict the sum index c' to each particle type with an overall extra factor on the right-hand side (RHS) of this expression that accounts for the particle-type probability emission.

The generalization of Eq. (5) to accommodate one precompound stage between the GR and CN, namely, $2p$-$2h$, is done by a subdivision of Q space into Q_P (precompound) and Q_C (CN) projectors that generalize the transmission coefficient $T_{c'}$, including the np-nh stages:

$$T_{n,c'}=\tau_{n,c'}+\sum_{m=1}^{n-1}\mu_{mn}T_{m,c'}, \tag{6}$$

where the $\tau_{n,c'}$ describes the direct coupling of c' and np-nh subspace. Since the doorway hypothesis is made, the coupling between nonsuccessive stages can be ignored and, for the dominance of the statistical CN decay, remains assured, in a good approximation, when we ignore the feedback to c' terms. Then the $\overline{\sigma}_{cc'}$ assumes the simple form as in Ref. [12]:

$$\overline{\sigma}_{cc'}\simeq\tau^{D}_{c}\Bigg[(1-\mu_{DP})\frac{\tau^{D}_{c'}}{\sum_{c''}\tau^{D}_{c''}}+\mu_{DP}(1-\mu_{PC})\frac{\tau^{P}_{c'}}{\sum_{c''}\tau^{P}_{c''}}+\mu_{DP}\mu_{PC}\frac{\tau^{C}_{c'}}{\sum_{c''}\tau^{C}_{c''}}\Bigg], \tag{7}$$

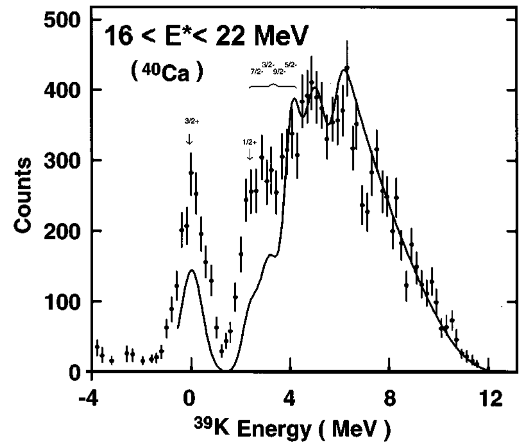

FIG. 1. Statistical contribution to ^{40}Ca E2GR decay (solid curve) compared to the experimental data.

where $\mu_{DP}=\Gamma^{\downarrow}_{DP}/\Gamma_D$ and $\mu_{PC}=\Gamma^{\downarrow}_{PC}/\Gamma_P$ are the mixing parameters which couple the GR to precompound and the precompound to the CN, respectively. The Γ_D and Γ_P width are defined in Eq. (3), noting that the most important couplings are those between successive stages. The $(1-\mu_{DP})$, $\mu_{DP}(1-\mu_{PC})$, and $\mu_{DP}\mu_{PC}$ factors give the semidirect, precompound, and statistical branching decays where the spreading to successive steps is measured by its respective mixing parameters. The application of Eq. (7) to the analysis of the experimental data furnishes information on the escape and spreading widths of the GR's decay and supplies, in a simple way, the contribution of the preequilibrium branching when this component is evident through specificity and selectivity of states in the residual nucleus. In this way, this kind of analysis can provide a selective test of the multipolarity admixture in the GR's excitations by reactions like hadron or heavy-ion scattering.

III. PROTON DECAY IN ^{40}Ca

The proton spectra from the decay of the E2GR in ^{40}Ca was calculated with Eq. (7). In what follows, we will refer to the first, second, and third terms in Eq. (7) as sd, pre, and st, standing for semidirect, preequilibrium, and statistical term, respectively. The E2GR in ^{40}Ca is split into two peaks centered at 14 and 17.5 MeV, with widths of 2 and 3 MeV, respectively, and with a proton threshold of $\sim$8.3 MeV. The experimental proton spectra was obtained by [21,22] in a ^{40}Ca$+^{40}$Ca reaction at 50 MeV/nucleon. The theoretical calculation was compared to the emitted proton spectra from the ^{40}Ca decay in the energy range of 16–22 MeV which leaves the residual nucleus ^{39}K in the range 0–13.7 MeV of excitation energy. For such a large interval of excitation energy of ^{39}K, the use of a continuum level density to describe the residual nucleus becomes necessary in the proton spectra calculations. Thus, the Fermi gas backshifted formula [23], with parameters extracted from Ref. [24], was utilized for energy levels above 5.8 MeV, and below this energy, the discrete energy levels of the ^{39}K [25] were used.

In Fig. 1, pure statistical calculation [only the st term in Eq. (7) with $\mu_{DP}=\mu_{PC}=1$] is presented in comparison with the experimental spectra. This calculation assumes that nei-

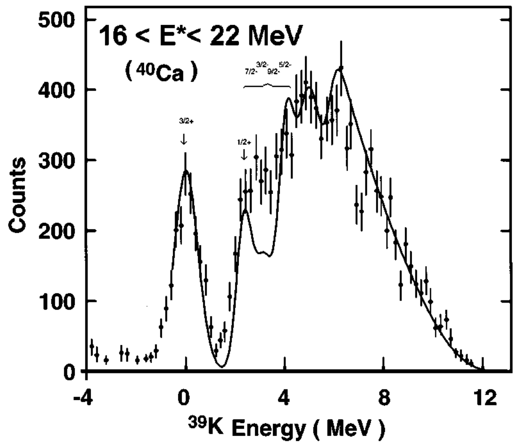

FIG. 2. The same as Fig. 1 for the semidirect and statistical contributions. Note that the population of the collective states in ^{39}K in the 3.6 MeV region still remains underestimated.

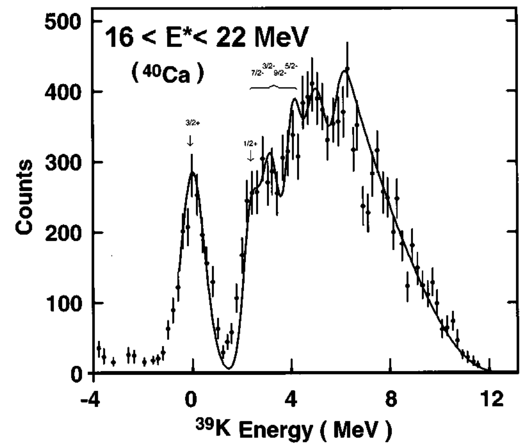

FIG. 3. The same as Fig. 1 with the all terms of Eq. (7). This figure shows that the role of the preequilibrium component is to give a contribution to the collective states in ^{39}K, giving a good fit with the experimental spectrum characterizing the precompound stage of the reaction.

ther semidirect nor preequilibrium components are present in the decay, accounting only for the compound nucleus evaporation. The normalization with the experimental data was performed for protons that populate the ^{39}K in energies above 4.2 MeV, where the dominance of statistical decay is most probable. In this calculation each proton line is represented by Gaussians to fit the experimental spectra to the normalization region. As we can see in Fig. 1 the calculation underestimates ($\sim$16%) the total number of protons, showing that the single-hole $3/2^+$ (ground state) and $1/2^+$ (first excited) and other nonpure single-hole states [26–30] in the 3.6 MeV region have a proton population leakage which forces us to conclude that other decay mechanisms must be important in this analysis to explain the measured spectra.

In Fig. 2 the sd term is added to the st term, $\mu_{PC}=1$ in Eq. (7). Here, we can observe that the ground state (g.s.) and the first excited state populations are increased with the inclusion of escape effects assigned to $1p$-$1h$ excitation modes in GR. This decay model is equivalent to a previous analysis [14,31] where the semidirect and statistical contributions are considered to explain the GR's decay mechanisms. The sd contribution represents approximately 11% (7% for the g.s. and 4% for the first excited state) of the total protons, noting that the analysis is based on the assumption of the independence of channel-particle-type emission [19]. The requirement of the preequilibrium component to explain the experimental data is clear in Fig. 2, since the only collective states, adjusted by the sd term, are those of pure holes in the residual nucleus.

Finally, Fig. 3 shows the complete calculation through Eq. (7) where the pre term is added to the calculations of Fig. 2. In Fig. 3 we observe that the preequilibrium contribution is crucial to give a good agreement with experimental data and only this term can raise the valley in the 3.6 MeV region missing in Fig. 2 so that the total proton count over the whole energy range remains preserved. This component, assigned to the collective state population, points to the remarkable evidence of the $1p$-$1h$ evolution to more complicated (e.g., $2p$-$2h$) excitation modes and their eventual decay.

The level separation was not performed since they are very close which allowed us to just estimate their summed average value corresponding to $\sim$5% of the total protons.

IV. CONCLUSION

The decay modes in GR are studied and the results show that the branchings of the semidirect and preequilibrium decays must be included in the spectra analysis together with the statistical calculations for the E2GR in ^{40}Ca proton decay. An important point is that one needs, to fit the experimental data, to consider the preequilibrium decay in the calculation which shows the presence of excitations more complicated than $1p$-$1h$ in the GR.

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