Escape width of the giant monopole resonance in ^{90}Zr

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The proton and neutron decay of the giant monopole resonance in ^{90}Zr is analyzed in terms of collective and statistical doorway states. For this purpose the hybrid model of the decay is used in the context of channel particle competition. The semidirect components are compatible with the particle-hole continuum random-phase-approximation calculations. The protons spectra are found to be predominantly statistical while the neutron spectra contain semidirect contributions. [S0556-2813(97)00203-3]

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The study of the decay properties of giant multipole resonances (GMR's) is of paramount importance for the unraveling of their dynamical and 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 width composed of two pieces: the ''escape width,'' representing the coupling of the GMR to the continuum, and the ''spreading width,'' which measures the degree of fragmentation of the strength, due to coupling to complicated intrinsic nuclear configurations (e.g., two-particle–two-hole) [1]. The first step of the reaction, namely the giant resonance population, is a coherent process in which one-particle–one-hole configurations act in phase, the other step is more complicated enough to call for a statistical treatment.

It has been a common practice to analyze the particle spectra originating from the decay of GMR with one of two extreme models. Both of which ignore the intermediate pre-equilibrium stages [2–5]. Such models assume the dominance of $\Gamma^{\uparrow}$, meaning that the GMR predominantly decays ''directly,'' or the predominance of $\Gamma^{\downarrow}$, which necessarily implies that the fragmentation of the resonance into the complex background is complete [3,4]. In the latter case the Hauser-Feshbach theory [6] is used in the analysis.

On the other hand, in the theory of the hybrid model [7], the GMR decay by particle emission accounts both for the direct component and the direct equilibrated compound nucleus part. This theory was only used in the analysis of exclusive data of the giant monopole resonance (E0GR) in ^{208}Pb [7,8]. This analysis is based on the equation

$$b_i=(1-\mu)\frac{\tau_{iD}}{\sum_j\tau_{jD}}+\mu\frac{\tau_{iC}+\mu\tau_{iD}}{\sum_j(\tau_{jC}+\mu\tau_{jD})}, \tag{1}$$

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

In the application of the above-mentioned theory for E0GR decay in ^{208}Pb [7,8] the meaning of the mixing parameter is completely connected with the statistical component of the neutron channels, since only these channels are open. In some particular situations where more than one type of channel is open, the connection with the statistical component of each channel is not possible, since in Eq. (1) it is necessarily the same for all types of channels. Furthermore,

TABLE I. Number of experimental levels (expt) compared with the calculated levels (theor) for ^{89}Y. Above 3.0 MeV only the total number of experimental levels is presented since no spin distribution is available.

Spin	1/2		3/2		5/2		7/2		$\geqslant$9/2		Total	
ΔE (MeV)	Theor.	Expt.	Theor.	Expt.	Theor.	Expt.	Theor.	Expt.	Theor.	Expt.	Theor.	Expt.
0–1	1	1	0	0	0	0	0	0	1	1	2	2
1–2	0	0	1	1	1	1	0	0	0	0	2	2
2–3	0	0	0	1	2	1	2	2	3	3	7	7
3–4	4	—	5	—	4	—	3	—	7	—	23	21
4–5	3	—	6	—	9	—	11	—	46	—	75	41
5–6	2	—	4	—	5	—	6	—	34	—	51	48

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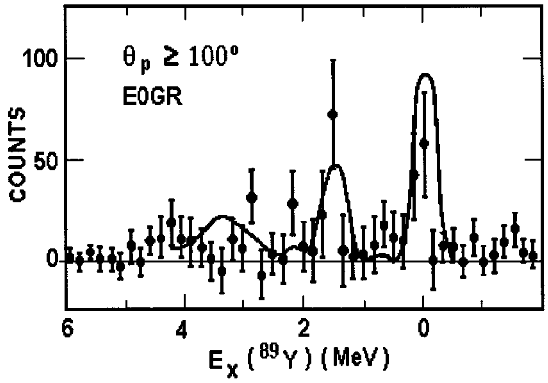

FIG. 1. The calculated protons spectrum (continuum line) using Eq. (2) is compared with the experimental data.

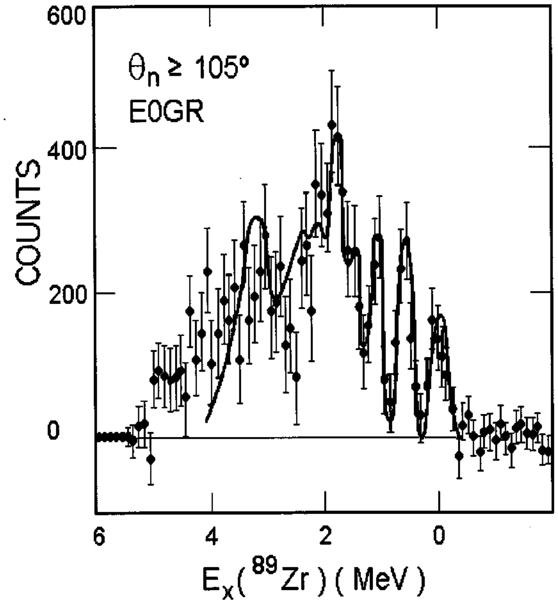

FIG. 2. The calculated neutrons spectrum (continuum line) using Eq. (2) is compared with the experimental data.

the analysis of experimental data is complicated when more than one type of particle channel is present, because all information for types of channels is required at the same time.

In order to resolve such difficulties we have developed [9] a generalization for the hybrid model which takes into account the separation and independence of the types of particle channel. In this model the parameter is composed of several μ_k's, belonging to each type of open channel, where the μ_k provides the respective branching. The final equation, obtained for the analysis of the experimental data is

$$b_i^k \approx (1-\mu_k) P_k \frac{\tau_{iD}^k}{\sum_j \tau_{jD}^k} + \mu_k P_k \frac{\tau_{iC}^k + \mu_k P_k \tau_{iD}^k}{\sum_j (\tau_{jC}^k + \mu_k P_k \tau_{jD}^k)}, \quad (2)$$

where μ_k is defined as

$$\mu_k = 1 - \frac{1}{P_k} \frac{\Gamma_k^{\uparrow}}{\Gamma}, \quad (3)$$

with P_k the emission probability of the kth particle (obtained from the experimental data) and $\Gamma_k^{\uparrow}$ is related with τ_{iD}^k. Further details are outlined in [9].

The aim of this work is to present a numerical application using Eq. (2) for the decay of the giant monopole resonance of ^{90}Zr [10].

The E0GR in ^{90}Zr has its centroid at 16.1 MeV excitation energy and presents a total width of $\Gamma = 3.1$ MeV. The neutrons, protons, and alpha are the possible particle emission channels for this energy. The most relevant ones are the protons and neutrons, with emission probability of $P_\pi = 0.1$ and $P_\nu = 0.88$, respectively [10].

The proton channels opens at $E_x = 8.36$ MeV, populating ^{89}Y at excitation energy of ~ 7.8 MeV. The level density for ^{89}Y in the proton spectra calculation, by means of Eq. (2), has been divided into two parts: for $0-3$ MeV, the energies and spins of experimentally measured levels [11,12] and above 3 MeV the predicted levels by the particle-vibrator model was used, coupling one proton to the ^{88}Sr core. We illustrate in Table I the level distribution for ^{89}Y predicted by the model. The calculated proton spectrum results are shown in Fig. 1. It was verified that the proton spectrum is compatible with the statistical decay, giving $\mu_\pi \simeq 1$, corresponding to a null escape for that channel. The experimental spectrum [10] has been measured with a resolution at 400 keV for the proton lines. The normalization takes into account the total number of protons in the energy interval $0 \leqslant E_x(^{89}\mathrm{Y}) \leqslant 4.5$ MeV.

The threshold for neutron decay is 11.98 MeV. This decay populates the energy levels in ^{89}Zr up to approximately 4.5 MeV. For this case, use has been made of experimental spins and energy levels [11,12] up to 2.1 MeV. Above this

TABLE II. Number of experimental levels (expt) compared with the calculated levels (theor) for ^{89}Zr. Above 2.0 MeV only the total number of experimental levels is presented since no spin distribution is available.

Spin	1/2		3/2		5/2		7/2		⩾9/2		Total	
ΔE (MeV)	Theor.	Expt.	Theor.	Expt.	Theor.	Expt.	Theor.	Expt.	Theor.	Expt.	Theor.	Expt.
0–1	1	1	0	0	0	0	0	0	1	1	2	2
1–2	0	0	1	3	2	3	1	1	3	1	7	8
2–3	3	—	3	—	4	—	5	—	23	—	38	28
3–4	4	—	9	—	10	—	12	—	31	—	66	23
4–5	8	—	17	—	24	—	27	—	126	—	202	11

TABLE III. Comparisons between the spectra based in Eq. (2), the continuum RPA method of [15] and the statistical calculations of [10].

k	i	E_{xi} (MeV)	Eq. (2) $\Gamma^{\uparrow}_{ki}$ (MeV)	RPA $\Gamma^{\uparrow}_{ki}$ (MeV)	[10] $\Gamma^{\uparrow}_{ki}$ (MeV)
	$9/2^+$	0.0	0.130	0.170	0.150
	$1/2^-$	0.59	0.095	0.0	0.0
	$3/2^-$	1.09	0.085	0.0	0.0
ν	$5/2^-$	1.45	0.100	0.330	0.0
	$\Gamma^{\uparrow}_{\nu}$ (MeV)		0.410	0.500	0.150
	μ_{ν}		0.850	–	–
π	$\Gamma^{\uparrow}_{\pi}$ (MeV)		0.0	0.020	0.0
	μ_{π}		1.0	–	–
$\nu+\pi$	$\Gamma^{\uparrow}$		0.410	0.520	0.150
	μ		0.848	–	–

TABLE IV. The Landau-Migdal residual interaction parameters and Woods-Saxon potential for continuum RPA calculations.

Landau-Migdal interaction				
C_0 (MeV fm^3)	f'_{0in}	f'_{0ex}	f'_{0in}	f'_{0ex}
300	-0.3	-2.45	0.60	1.50
	g_0	g'_0	R (fm)	a (fm)
	0.55	0.70	5.10	0.60
Woods-Saxon potential				
Particle	V_0 (MeV)	$V_{l\sigma}$ (MeV fm)	R_{WS} (fm)	a_{WS} (fm)
π	55.3	25.5	5.69	0.70
ν	48.7	25.5	5.69	0.70

energy the predicted levels are from the coupling of two protons and a neutron hole to ^{88}Sr [13]. The predicted level distribution is shown in Table II. The calculated neutrons spectrum has been normalized in relation to the total number of neutrons in the energy interval $0 \leqslant E_x(^{89}\mathrm{Zr}) \leqslant 4.2$ MeV, using a variable energy resolution of 250–500 keV and the detector efficiency curve [10]. The fitting of our results to the experimental data [10] has been presented in Fig. 2. It was possible to verify that $\sim$16% of the emitted neutrons populate the hole states at the lowest energies in ^{89}Zr through a semidirect contribution, obtaining $\mu_{\nu}=0.85$, and an escape width of 410 keV, distributed among the levels $9/2^+$, $1/2^-$, $3/2^-$, and $5/2^-$ in ^{89}Zr (see Table III). The calculations were performed with the optical potential parameters from [14].

Using a purely statistical calculation [10] it has been shown that the proton decay is statistical and the neutron decay presents $\sim$5% of the semidirect contribution populating the ground state ($9/2^+$) in ^{89}Zr, corresponding to an escape width of $\sim$150 keV. These results are in accordance with ours regarding the proton spectra and the neutron escape width to the ground state in ^{89}Zr. However, our analysis led to a semidirect contribution for the population of the $1/2^-$, $3/2^-$, and $5/2^-$ levels in ^{89}Zr not predicted in [10] (see Table III). One of the reasons for this disagreement is due to a difference in the energy level densities in ^{89}Zr. In order to describe ^{89}Zr, above 2.1 MeV, we used the particle-vibrator model in our calculations while in [10] a continuum Fermi gas level density was used. Of course, the accuracy of the results will depend on how well the level density is represented. In our particular case the excitation energies of the residual nuclei is not high (5–6 MeV) enough so that level density would be well represented by a continuum level density [3]. Another difference in the analysis is that we have included the escape effects directly in the calculations of the spectra, as has been illustrated in Eq. (2), while [10] is a purely statistical calculation.

The results which have been obtained using Eq. (2) for the E0GR decay in ^{90}Zr are in agreement with the continuum RPA calculations with continuum descretization methods presented in [15]. These calculations are done with Woods-Saxon potentials for protons and neutrons and the Landau-Midgal residual interaction parametrization presented in Table IV. The microscopic calculation predict a centroid of the E0GR at 15.84 MeV, with the escape width of $\Gamma^{\uparrow}=520$ KeV, exhausting about 50% of the classical EWSR in the 0–30 MeV interval. The width $\Gamma^{\uparrow}$, composed by $\Gamma^{\uparrow}_{\pi}=20$ keV and $\Gamma^{\uparrow}_{\nu}=500$ keV, is in agreement with escape widths obtained with Eq. (2). However, they show small deviations in relation to the neutron partial width for the $1/2^-$, $3/2^-$, and $5/2^-$ neutrons holes, as has been presented in Table III.

In this work we have shown that the analysis of the emitted particle spectra in the decay of the GR is much simplified and transparent when we utilize the separation of the type of particles (as proposed in [9]) in the general model of [7]. One advantage is that one could analyze the spectra for each type of particle independently of each other. Consequently, it is possible to adjust the partial μ_k (and the correspondent escape width) in each spectrum.

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