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Spreading widths of giant resonances in spherical nuclei: Damped transient response

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We propose a general approach to describe spreading widths of monopole, dipole, and quadrupole giant resonances in heavy and superheavy spherical nuclei. Our approach is based on the ideas of the random matrix distribution of the coupling between one-phonon and two-phonon states generated in the random-phase approximation. We use the Skyrme interaction SLy4 as our model Hamiltonian to create a single-particle spectrum and to analyze excited states of the doubly magic nuclei ^{132}Sn, ^{208}Pb, and ^{310}126. Our results demonstrate that the approach enables to us to describe a gross structure of the spreading widths of the giant resonances considered.

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Damping of collective motion in finite many-body quantum systems is one of the topical subjects in mesoscopic physics. The question of how, for example, multipole giant resonances (GRs) in nuclei [1] and metal clusters [2] dissolve their energy is still not well understood. There is, however, a consensus of opinion that, in particular, in a nucleus, once excited by an external field, a GR progresses to a fully equilibrated system via direct particle emission and by coupling to more complicated states produced by the intrinsic motion of nucleons (see, for example, Ref. [3]). The former mechanism gives rise to the escape width Γ_p. It is expected that the decay evolution along the hierarchy of more complex configurations till compound states determines spreading width Γ. A full description of this decay represents a fundamental problem which is, however, difficult to solve (if even possible at all) due to the existence of many degrees of freedom.

In general, the description of spreading width in mesoscopic systems is based on the study of the electromagnetic strength distribution (strength function) [4] in some energy interval. This interval should be large enough to catch hold of basic features of a GR under investigation. Note that, in deformed systems, the experimental widths are systematically larger and may develop a two- or three-peak structure. In this paper we consider only spherical nuclei in order to highlight a generic nature of the width Γ in monopole, dipole, and quadrupole resonances in heavy and superheavy systems.

The nuclear shell model may be used to analyze spreading widths of GRs. However, the complexity of the calculations increases rapidly with the size of the configuration space. This fact severely restricts the feasibility of shell-model calculations for heavy and superheavy nuclei. In addition, even for a medium ^{48}Ca isotope, the state-of-art shell-model calculations [5], which operate with the Hamiltonian matrices of a huge dimension, produce questionable results for the dipole GR. Although these calculations reproduce reasonably well its peak position and peak width, the enhancement of the classical Thomas–Reiche–Kuhn sum rules is too overestimated. As a result, the number of shell-model studies, in particular, dipole GRs in heavy and superheavy nuclei are limited and rather focused on details of the low-energy region (see, e.g., Ref. [6]).

The success of random matrix theory (RMT) [7–12], which is based on universal features in the spectra of complex quantum systems, gives hope that light will be shed on the spectral properties and the distribution of the transition-strength properties of GRs, when specific details become not of a primary importance. As is well known, RMT assumes only that a many-body Hamiltonian belongs to an ensemble of random matrices that are consistent with the fundamental symmetries of the system such as parity, rotational, translational, and time-reversal symmetries. We believe that it is quite suitable for our aim; namely, to provide a generic principle for the decay of highly excited states with angular momentum and parity: $J^{\pi} = 0^+, 1^-, 2^+$. On the other hand, to understand the realistic fragmentation of high-lying states over complex configurations, observed as structures in the spreading width, it is necessary also to exploit a realistic nuclear structure model. It should be based on the microscopic many-body theory, where the effects of the residual interaction on the statistics must be studied in large model spaces. Introducing a residual interaction in general implies a transition to the Gaussian orthogonal ensemble (GOE)—properties above some excitation energy [13]. In fact, recent analysis of 151 experimental nuclear levels up to the excitation energy of $E_x = 6.2$ MeV in ^{208}Pb indicates already that the spectral properties are described by the GOE due to a residual interaction, even though there is a small admixture of regular dynamics brought about by the low-lyings states [14].

The quasiparticle-phonon model (QPM) [15] offers an attractive framework for such studies. We will use the modern development of the QPM, a finite rank separable approximation (FRSA) [16]. That approach employs the Skyrme forces to calculate the single-particle (sp) spectrum and the residual interaction in a self-consistent manner in order to avoid any artifacts [17]. As an example of the parameter set, we consider the widely used SLy4 [18] which is adjusted to reproduce the nuclear matter properties, as well as nuclear charge radii, binding energies of doubly magic nuclei. This set shifts the island of stability towards high charge numbers around $^{310}_{184}$126 [19]. Evidently, another parameter set can be used as well for our purposes. The continuous part of the sp spectrum is discretized by diagonalizing the Hartree–Fock Hamiltonian on a harmonic-oscillator basis. The cutoff of the continuous part is at the energy of 100 MeV.

The residual particle-hole interaction is obtained as the second derivative of the energy density functional with respect to the particle density. By means of the standard procedure [20] we obtain the familiar equations of the random-phase approximation (RPA) in the one particle-one hole (1p-1h) configuration space. The eigenvalues of the RPA equations are found numerically as the roots of a relatively simple secular equation within the FRSA [16]. Being a linear combination of 1p-1h states, the RPA solutions are treated as quasibosons with quantum numbers λ^π. Among these solutions there are one-phonon states $\omega_{\lambda i}$ corresponding to collective GRs and pure two-quasiparticle states. The configurations with various degrees of complexity can be built by combining different one-phonon configurations $\lambda_1^{\pi_1}$, $\lambda_2^{\pi_2}, \ldots$ of fixed quantum number λ^π. As a result, one obtains the n-phonon components $[\lambda_1^{\pi_1} \otimes \lambda_2^{\pi_2} \otimes \cdots \otimes \lambda_n^{\pi_n}]_{\lambda^\pi}$ of the wave function. The diagonalization of the model Hamiltonian in the space of the one-phonon and complex configurations produces eigenstates of excited states. These states carry information on the fragmentation of the one-phonon component over complex configurations in the resulting eigenfunction.

A natural question arises: what degree of complexity of configuration should be enough in order to understand a gross structure of a particular GR which data are available in modern experiments? In addition, once this complex configuration is defined one can further ask about statistical properties of states that compose a GR strength distribution.

In the actual calculations of the GRs strength distributions in the spherical nuclei ^{132}Sn, ^{208}Pb, and ^{310}126 considered as examples, we have included in our model space different multipoles $\lambda^\pi = 0^+, 1^-, 2^+, 3^-, 4^+$. Tentative estimates for the position of the resonance centroids E_c and the spreading width Γ are defined by means of the energy-weighted moments $m_k = \sum B(E\lambda)E^k$: (i) $E_c = m_1/m_0$, (ii) $\Gamma = 2.35[m_2/m_0 - (m_1/m_0)^2]^{1/2}$ (see, for example, Ref. [21]). Note that the coefficient 2.35 has its roots in the experimental definition of the width (full width at half maximum) related to the variance of the Gaussian (see, for example, Ref. [3]). Next, we construct various combinations of two-phonon states $\omega_{\lambda_1 i_1} + \omega_{\lambda_2 i_2}$ to define the energy interval for location of the resonance width of fixed quantum number λ^π, taking 95% of the energy-weighted sum rule symmetrically around the centroid's position (E_c). It is noteworthy that, for all GRs, considered in the present paper, the matrix elements for direct excitation of two-phonon components from the ground state are about two orders of magnitude smaller relative to ones for the excitation of one-phonon configurations. On the other hand, the density of these complex configurations is much higher than the one-phonon density and contributes essentially to statistics of the final states.

From our preliminary analysis of complex structure observed in the region of the isoscalar giant monopole resonance (ISGMR) with $J^\pi = 0^+$ of the doubly magic nucleus ^{208}Pb [22] we have found that the spectrum can be explained as a result of mixing of one- and two-phonon components of the wave function, i.e.,

$$\Psi_\nu(JM) = \left\{ \sum_i R_i(J\nu) Q^+_{JMi} + \sum_{\lambda_1 i_1 \lambda_2 i_2} P^{\lambda_1 i_1}_{\lambda_2 i_2}(J\nu) \left[Q^+_{\lambda_1 \mu_1 i_1} Q^+_{\lambda_2 \mu_2 i_2} \right]_{JM} \right\} |0\rangle,$$

where $Q^+_{\lambda\mu i}|0\rangle$ is the RPA excitation having energy $\omega_{\lambda i}$, λ denotes the total angular momentum, and μ is its z projection in the laboratory system.

In the case of the phonon-phonon coupling (PPC) the variational principle leads to a set of linear equations for the unknown amplitudes $R_i(J\nu)$ and $P^{\lambda_1 i_1}_{\lambda_2 i_2}(J\nu)$ (see details in Ref. [23]):

$$(\omega_{Ji} - E_\nu) R_i(J\nu) + \sum_{\lambda_1 i_1 \lambda_2 i_2} U^{\lambda_1 i_1}_{\lambda_2 i_2}(Ji) P^{\lambda_1 i_1}_{\lambda_2 i_2}(J\nu) = 0, \tag{1}$$

$$\sum_i U^{\lambda_1 i_1}_{\lambda_2 i_2}(Ji) R_i(J\nu) + 2\left(\omega_{\lambda_1 i_1} + \omega_{\lambda_2 i_2} - E_\nu\right) P^{\lambda_1 i_1}_{\lambda_2 i_2}(J\nu) = 0. \tag{2}$$

To resolve this set it is required to compute the coupling matrix elements

$$U^{\lambda_1 i_1}_{\lambda_2 i_2}(Ji) = \langle 0| Q_{Ji} H \left[Q^+_{\lambda_1 i_1} Q^+_{\lambda_2 i_2} \right]_J |0\rangle \tag{3}$$

between one- and two-phonon configurations.

A few remarks are in order. Our approach is similar to the particle-vibration coupling (PVC) model based on the Green's function method (see for a recent review Ref. [24]) that has been used in the study of the monopole [25] and the quadrupole [26] GR widths in ^{208}Pb with the aid of Skyrme forces. Note that the PPC includes as well the coupling of one-phonon state with two-particle two-hole states, important in the PVC model, as a particular case (see discussion in Chapter 4.3 of the textbook [15]). However, a consistent realization of the QPM as well as the PVC model (which closely follows the concept of the "conserving approximation" introduced by Baym and Kadanoff [27]) is very difficult to implement numerically. In particular, in order to let the two-phonon components of the above wave function obey the Pauli principle the exact commutation relations between the phonon operators should be taken into account [15]. As a result, this would lead to the "dressed" two-phonon energies, which are not accounted for here. As we will see below, the random matrix approach enables to us to effectively avoid this problem.

We start our discussion from the analysis of the spreading width of the isovector giant dipole resonance (IVDGR) in the spherical ^{208}Pb nucleus, since it is the best-known example of nuclear vibrations. The coupling (the PPC) of the

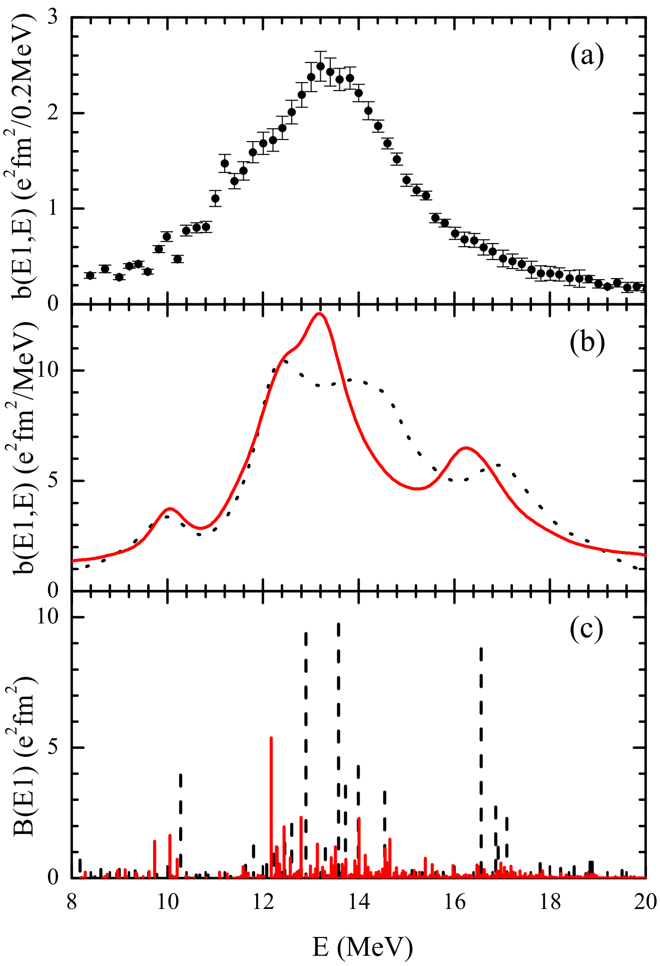

FIG. 1. ^{208}Pb: (a) experimental $B(E1)$ strength distribution. (b) Comparison of the results obtained by means of the microscopic (dotted line) and the random (solid line) coupling matrix elements between the one- and two-phonon configurations. (c) $B(E1)$ strength distribution for one-phonon states (dashed line) and for the PPC case. The smoothing parameter 1 MeV is used for the strength distribution described by the Lorentzian function. The experimental data are taken from Ref. [28].

one-phonon states with an intermediate complex background of two-phonon states yields a strong redistribution of the one-phonon dipole strength in the region of the IVDGR [see Fig. 1(c)]. It suppresses the high-lying one-phonon strength near (∼17 MeV) and pushes this strength down (see also Ref. [29]). As a result, we obtain a reasonably good description of the dipole strength distribution over the resonance localization region [compare Figs. 1(a) and 1(b)]. It appears that the presence of two-phonon components in our wave function, in addition to the one-phonon components, already enables us to describe the gross strength distribution of the typical dipole response in the heavy spherical nucleus ^{208}Pb. Similar conclusions have been drawn on the basis of shell-model calculations for the states above 8 MeV in Ref. [6].

The relatively broad realistic distribution seen in Fig. 1 indicates that many two-phonon configurations contribute to the fragmentation process. Indeed, the RMT measurements such as the nearest-neighbor spacing distribution (NNSD) and the spectral rigidity Δ_3 indicate a transition towards the GOE when the coupling is switched on (see Figs. 3 and 4 in Ref. [22] for the ISGMR). Evidently, the extension of the wave function to more complex configurations would increase the fragmentation of the one-phonon strength over many excited states. This complexity suggests an approach from random matrix theory to describe the fragmentation of the transition strength between the RPA states and the ground state.

The coupling of the phonon states to more complex background states can be described by a simple doorway-state Hamiltonian (cf Ref. [4])

$$H_{J^\pi} = H_d + H_b + V, \tag{4}$$

where H_d describes the doorway states, H_b describes the background states, and V describes the coupling between doorway states and background states. The RPA-phonon states constitute the doorway states, $H_d = \sum_i \omega_{Ji} Q^+_{Ji} Q_{Ji}$, and the background states are two-phonon and possibly more complex states, with eigenstates $H_d|d\rangle = \omega_d|d\rangle$ and $H_b|b\rangle = e_b|b\rangle$, respectively. The Hamiltonian H_{J^π} represents a set of good quantum numbers J^π, and the RPA phonons as well as all background states fulfill these quantum numbers. We assume no coupling between different doorway states or between different background states, $\langle d|V|d'\rangle = 0$ and $\langle b|V|b'\rangle = 0$, but all coupling takes place between the doorway states and the complex background states, $\langle d|V|b\rangle = V_{db}$.

Similar ideas were discussed in Ref. [30] where some limiting analytical estimates for the GDR strength function were obtained by coupling a collective state to chaotic background states. Our aim is to describe microscopically the one-phonon GR states for arbitrary multipolarity and attempt a random-matrix-inspired treatment of the coupling to complex surrounding states, here viewed as two-phonon states. The quality of the random treatment can then be studied by comparing results with the microscopic PPC model predictions.

The doorway states are thus taken from the microscopic RPA calculation for the isoscalar or isovector J^π mode providing energies ω_d and transition matrix elements to the ground state ($|0\rangle$), $B_d = \langle d|\mathcal{M}_{J^\pi}|0\rangle$, via the transition operator $\mathcal{M}_{J^\pi}$. No transition can occur between a background state and the ground state, $0 = \langle b|\mathcal{M}^\pi_J|0\rangle$. After diagonalization of the Hamiltonian H_{J^π}, the transition strength of the doorway states is fragmented on all states, and provides the full transition strength distribution.

The modeling of background states, e_b, and couplings, V_{db}, can be performed on different levels of approximation. In the PPC model, the background energies e_b are obtained as the sum of two RPA phonon energies, $\omega_{\lambda_1} + \omega_{\lambda_2}$, coupled to J^π. The coupling matrix elements V_{db} are subsequently obtained from Eq. (3). To account for underlying complexity we now replace these matrix elements by a random coupling. The parameter that determines the strength of the coupling is the rms value of the matrix elements, $\sigma = (\langle V^2_{db}\rangle)^{1/2}$. The actual distribution of the random interaction is not important, as long as it is symmetric, $\langle V_{db}\rangle = 0$. While the microscopic matrix elements follow a truncated Cauchy distribution, we chose a Gaussian

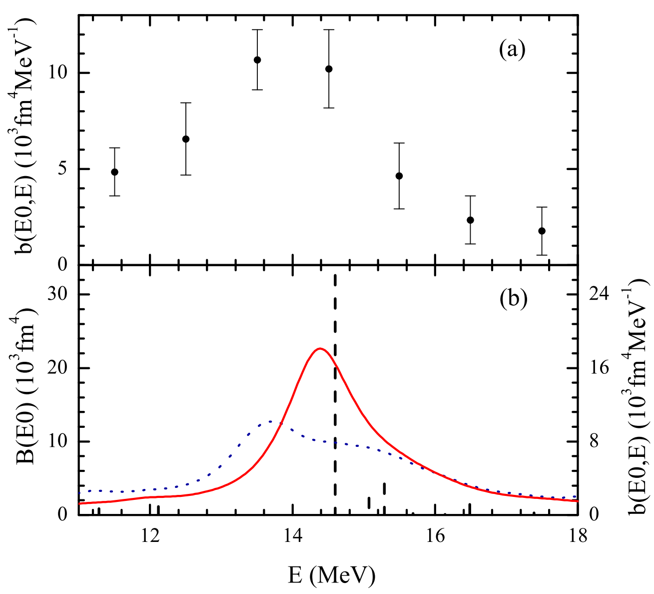

FIG. 2. The same as Fig. 1, in the case of ISGMR in ^{208}Pb. The experimental data are taken from Ref. [31].

distribution for the random interaction,

$$P(V) = \frac{1}{\sigma\sqrt{2\pi}} \exp \frac{-V^2}{2\sigma^2}. \quad (5)$$

Solutions of H_{J^π} are ensemble averaged over the random interaction and give the transition strength distribution.

Choosing the strength of the random interaction from the microscopic calculation of coupling matrix elements, which is the rms value $\boldsymbol{\sigma_c}$ of the coupling matrix elements given by Eq. (3), we get the $B(E1)$ distribution strength of IVGDR for ^{208}Pb. It is noteworthy that the comparison of the strength distributions obtained with the aid of the PPC and the random distribution of the matrix elements demonstrates a remarkable similarity [see Fig. 1(b)]. Moreover, by means of the latter distribution (5) we reproduce the experimental strength distribution of the IVGDR as well [compare Figs. 1(a) and 1(b)].

The RPA analysis provides the location of the ISGMR in ^{208}Pb in the energy region $E_x = 10.5$–18.5 MeV. The PPC yields a detectable redistribution of the ISGMR strength in comparison with the RPA results. It results in the 1 MeV downward shift of the main peak (see Fig. 2). Our analysis shows that the major contribution to the strength distribution is brought about by the coupling between the $[0^+]_{\rm RPA}$ and $[3^- \otimes 3^-]_{\rm RPA}$ components. In contrast, the use of the random matrix distribution yields the backshifting of this peak. Evidently, in this case there is only an average strength that does not produce any preferences in the coupling between one- and two-phonon states of different one-phonon nature. The strength distribution of the ISGMR obtained in this case is rather close to the experimental distribution [31].

In the same manner we calculate and compare different estimations for the strength distribution of the GRs in ^{132}Sn and ^{310}126 nuclei. The results of calculation and comparison with the experimental data and the empirical systematics are displayed in Table I. The description of the spreading width by means of the PPC and the random distribution (5) provide similar results for the ISGMR and IVGDR in all considered nuclei. For the isoscalar giant quadrupole resonance (ISQGR) the PPC yields the widths that are larger relative to those produced by the random distribution. Reliable experimental measurements are required in order to remove systematic uncertainties in experimental analysis based on optical potentials (see also the discussion in Ref. [26]).

Considering the interaction strength as a parameter, we investigate the complexity of the energy states in terms of the NNSD by studying the Brody mixing parameter [7] q versus σ. A smooth increase is found from regularity ($q = 0$; Poisson statistics) when $\sigma = 0$ to chaos ($q \approx 1$; GOE) when $\sigma = \sigma_r$, where the critical value σ_r depends on considered nucleus and the type of GR. It is remarkable that the onset of chaos appears at a σ value very similar to the interaction strength of the

TABLE I. Characteristics of the giant multipole resonances for ^{132}Sn, ^{208}Pb, and ^{310}126 nuclei: centroid energies E_c and the spreading widths Γ calculated with the RPA and RPA plus phonon-phonon coupling with the microscopic (PPC) and random distribution of coupling matrix elements (Random) are compared with available experimental data [31–34]. The values of E_c and Γ have been computed in corresponding energy intervals ΔE. For comparison the centroid energy and width values from the empirical systematics (Syst.) are presented [33,35,36].

		E_c (MeV)					Γ (MeV)					ΔE (MeV)
		Expt.	Syst.	Theory			Expt.	Syst.	Theory			
				RPA	PPC	Random			RPA	PPC	Random	
ISGMR	^{132}Sn		15.71	16.8	16.6	16.7			2.7	4.7	3.4	12–21
ISGMR	^{208}Pb	13.7 ± 0.1	13.50	14.7	14.4	14.6	3.3 ± 0.2		1.9	3.9	2.7	10.5–18.5
		13.96 ± 0.20					2.88 ± 0.20					
ISGMR	^{310}126		11.82	12.7	12.7	12.7			1.4	3.0	1.8	9.5–16
IVGDR	^{132}Sn	16.1 ± 0.7	15.26	15.5	15.4	15.3	4.7 ± 2.1	4.67	4.9	5.0	5.2	11–20
IVGDR	^{208}Pb	13.43	13.73	14.0	14.0	13.8	4.07	4.15	4.6	4.9	4.8	9.5–18.5
IVGDR	^{310}126		12.53	12.6	12.6	12.4		3.80	4.3	4.4	4.7	8.5–17.5
ISGQR	^{132}Sn		12.71	14.8	14.7	14.7		3.91	2.1	4.0	2.6	10–20
ISGQR	^{208}Pb	10.89 ± 0.30	10.92	13.0	13.0	13.0	3.0 ± 0.3	3.04	1.4	3.1	2.1	8–18
ISGQR	^{310}126		9.56	11.5	11.4	11.4		2.43	1.2	2.7	1.7	8–16

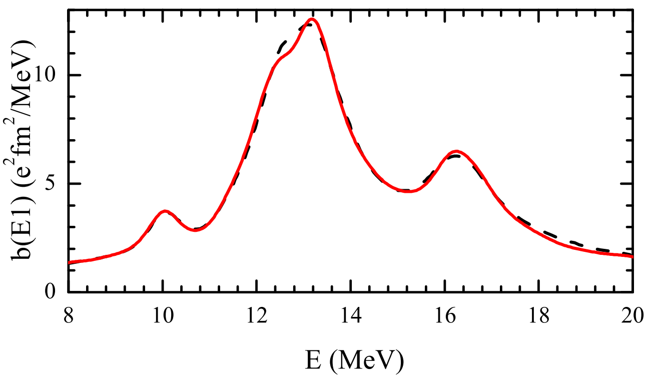

FIG. 3. $B(E1)$ strength distribution of ^{208}Pb: comparison of the results obtained by means of the random coupling matrix elements between the one- and two-phonon configurations. Results are shown of the calculations [see Eqs. (1) and (2)] with the energies $\omega_{\lambda_1 i_1} + \omega_{\lambda_2 i_2}$ (solid line) and with random GOE-generated two-phonon energies (dashed line). The smoothing parameter 1 MeV is used for the strength distribution described by the Lorentzian function.

microscopic phonon coupling model. We thus find that $\sigma_c \approx \sigma_r$ for each considered case. A way to chose the strength of the random interaction may thus be to find the σ value where the GOE properties appear, σ_r (practically defined as $q = 0.95$), rather than performing the full microscopic PPC calculation.

While the NNSD provides information about correlations on short energy scales, the spectral-rigidity measure Δ_3 characterizes long-range correlations between the energy levels. For the coupling strength σ_c ($\approx \sigma_r$), full short-range GOE correlations were found in the NNSD. The spectral rigidity Δ_3 only reproduces the GOE distribution $\bar{\Delta}_3(L) \approx \frac{1}{\pi^2}(\ln L - 0.0687)$ up to an L value of $L_{\max}$. For the IVGDR of ^{208}Pb we find $L_{\max} = 7$. This implies long-range GOE correlations in the strength distribution around the centroid energy within an energy range of about $L_{\max}/\rho(E_c) = 0.2$ MeV, where ρ is the density of background states. Consequently, only correlations beyond this energy range may provide specific structure information. Note, however, that the smoothing (1 MeV) smears out the strength effectively over more background states, which are not considered in the model. As a result, the correlation energy obtained by means of $L_{\max}$ is expected to be larger.

Since the energy spectrum shows full GOE properties when the appropriate coupling strength has been included, another step in the doorway state model can be introduced. Instead of calculating the background-state energies with the aid of the RPA calculations, one might employ random GOE-generated energies, following a smooth level-density function of background states, which on the average agrees with the density of two-phonon states. The resulting strength distribution calculated in this way coincides perfectly with the case when microscopic background energies are included (see Fig. 3). This implies that the exact position of the two-phonon energies is unimportant for the description of the gross structure of the GRs, and the complex RPA calculation of two-phonon energies may be replaced by random-matrix-generated energies. In addition, the obtained results demonstrate an expected negligible importance of the Pauli-principle dressing of two-phonon energies on the gross structure of the considered widths. This further simplifies the model and provides possibilities to calculate spreading widths of giant resonances in a quite general way.

In summary, we suggest a way to describe spreading widths of GRs by including the coupling between one- and two-phonon states. A detailed shell structure is included on the (one-phonon) RPA level with a Skyrme interaction while the strength fragmentation is treated with ideas from random-matrix theory: the coupling between one- and two-phonon states is generated by means of the random distribution of coupling matrix elements (5), and the energies of the two-phonon states are generated from the GOE distribution. For the studied cases we find that the coupling strength can be obtained from the GOE limit of the NNSD of spectra generated by the coupling between one- and two-phonon states, characterized by the same quantum number J^π.

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