Decay of giant resonances

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The quasiparticle–phonon model is used to calculate the partial widths for the γ decay of quadrupole and hexadecapole resonances in ^{90}Zr and ^{208}Pb to low-lying states of these nuclei. It is concluded that complex configurations play an important part in wave functions when the decay properties of highly excited states are correctly described. It is shown that core polarization ensures that the decay of isovector resonances is more intense than that of isoscalar resonances.

Intensive studies of highly excited nuclear states in different reactions have led to extensive experimental data on the integral characteristics of giant and single-particle resonances.[1–5] Theoretical studies of such resonances lead to the conclusion that the coupling between simple and complex configurations plays a dominant role in the decay of the resonances.[6–11] Despite the numerous experiments performed during the last decade, there is considerable uncertainty in the integral strength of states deduced from such data because of the arbitrary way in which the background is subtracted. Moreover, inelastic scattering of particles by nuclei provides mostly information on simple configurations forming the highly excited states. This means that the partial channels for the decay of highly excited states must be investigated in any study of the fine structure of such states, and their role in forming complex components of wave functions must be examined.

The background problem can be obviated by performing experiments in which the final reaction products are counted in coincidence. Examples of this type of experiment can be found in the review literature.[2,3] A very promising method of studying the structure of highly excited states is to count γ rays in coincidence with the inelastically scattered particle. For example, γ decays are dominated by electric dipole transitions, so that by defining the final states it is possible to select high-lying states with particular spins and parities. The first experimental studies of the γ decay of the giant isoscalar quadrupole resonance in ^{208}Pb (Refs. 12–14) and of deep hole states[15,16] have clearly demonstrated the possibilities of this approach.

This paper is devoted to an analysis of the above-mentioned experimental data, using microscopic calculations designed to establish the structural properties of giant resonances. All the calculations were performed within the framework of the quasiparticle–phonon model (QPM), described in detail in Refs. 17 and 18. The wave function for the excited state of an even–even nucleus, which includes the coupling between simple (single-phonon) and complex (two-phonon) configurations, has the following form in the QPM:

$$\Psi_\nu(JM)=\Big\{\sum_i R_i(J\nu)Q^+_{JMi} + \sum_{\substack{\lambda_1 i_1\\ \lambda_2 i_2}} P^{\lambda_1 i_1}_{\lambda_2 i_2}(J\nu)\,[Q^+_{\lambda_1\mu_1 i_1}Q^+_{\lambda_2\mu_2 i_2}]_{JM}\Big\}\Psi_0, \qquad (1)$$

where $Q^+_{\lambda\mu i}$ is the operator for the creation of a phonon of multipolarity λ with projection μ, order number i, and energy $\omega_{\lambda i}$ determined in the random-phase approximation, and Ψ_0 is the phonon vacuum, taken as the ground state of the even–even nucleus.

The spectrum of excited states $\eta_{J\nu}$ described by the wave function (1), and also the coefficients R and P, are determined by solving the corresponding secular equation.[18] For moderate and high excitation energies, for which the level density is relatively high, it is convenient to use the strength function

$$b(\Phi,\eta)=\sum_\nu |\Phi_{J\nu}|^2\frac{1}{2\pi}\frac{\Delta}{(\eta-\eta_{J\nu})^2+\Delta^2/4}. \qquad (2)$$

Here $\Phi_{J\nu}$ is the amplitude for the excitation of the state $\Psi_\nu(JM)$ in a given physical process, and Δ is the energy interval within which the average is evaluated. A detailed account of the method of strength functions is given in Ref. 18. We used the program GIRES[19] in our numerical calculations with the single-particle spectrum and the Woods–Saxon potential, as in our previous paper.[20] This spectrum is a modification of that obtained with the parameters given in Ref. 21. It was varied until the QPM wave functions provided a description of the energies of low-lying collective levels, the probabilities of electromagnetic transitions from these states to the ground state in ^{208}Pb, and the energies and spectroscopic factors of the levels of the neighboring even nuclei. At the same time, the multipole–multipole interaction constant was chosen in the Bohr–Mottelson form. The ratio of the isoscalar constant of the residual forces to the isovector constant was determined from the position of the giant dipole resonance. The resulting single-particle spectrum includes all the quasistationary levels up to the centrifugal barrier with given $l\leqslant 9$. The completeness of the single-particle basis was tested by demanding that it provided the correct description of the probabilities of electromagnetic

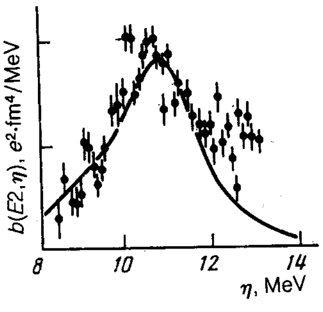

FIG. 1. Strength function for $E2$ transitions from the ground state to the states of the isoscalar GQR in ^{208}Pb. The solid curve shows the QPM calculations with $\Delta = 1$ MeV. The points represent the experimental data from Ref. 22.

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TABLE I. Integral characteristics of $E2$ and $E4$ resonances in ^{208}Pb.

J^π	Эксперимент			Theory		
	E_x, MeV	Γ, MeV	EEWSR, %	E_x, MeV	Γ, MeV	EERSR, %
2+ 4+	10.5–10.9 ~10.9	2.4–3.0 ~4.0	60–80 10–30	10.6 10.9	3.1 3.2	67 16

transitions without relying on effective charges.

Let us first consider how the quasiparticle–phonon model describes the integral characteristics of giant multipole resonances such as the position, the total width, and the exhaustion of the energy-weighted sum rule (EEWSR). We begin with the giant quadrupole resonance (GQR). Systematic reviews of experimental data on the excitation of the isoscalar GQR show that its energy is $E_x \sim 63A^{-1/3}$ MeV and that the isoscalar EEWSR is 50–100%. Existing energies of isovector GQRs are consistent with the expression $E_x \sim 110A^{-1/3}$ MeV.

Figure 1 shows the calculated strength function $b(E2,\eta)$ of the intensity distribution for $E2$ transitions in ^{208}Pb. It was obtained by taking into account the coupling between one- and two-phonon states, and also the experimental data[22] on the ^{208}Pb$(e,e'n)$ reaction. The calculations were performed for $\Delta = 1$ MeV. The $E2$ strength distribution exhibits a fine structure as Δ is reduced (see the calculations with $\Delta = 0.2$ MeV in Ref. 23), but the resonance width changes very little. It is clear from the figure that the distribution of the $E2$ strength in the region of the GQR is satisfactorily reproduced by the calculations. The integral characteristics of the $E2$ and $E4$ resonances in ^{208}Pb are listed in Table I. The resonance widths were calculated from the standard formula for the Gaussian distribution.[18] As we have already noted, the principal physical reason for the large widths is the coupling between the simple particle–hole and more complicated configurations. It was shown in Ref. 24 that coupling with the two-phonon states will alone produce the correct description of the widths in the QPM. The widths associated with the emission of nucleons into the continuum in the case of heavy nuclei are significantly smaller. They amount to a few tens of keV. This is clearly demonstrated in Ref. 25 in which the single-particle continuum is taken into account exactly in the coordinate representation.[26,27]

It was found in the experiments reported in Ref. 2 that the region of localization of the isoscalar GQR contains a hexadecapole resonance with 10–30% EEWSR. Our calculations show that, for the $E4$ resonance, $E_x = 10.9$ MeV, $\Gamma = 3.2$ MeV, and the EEWSR amounts to 16%.

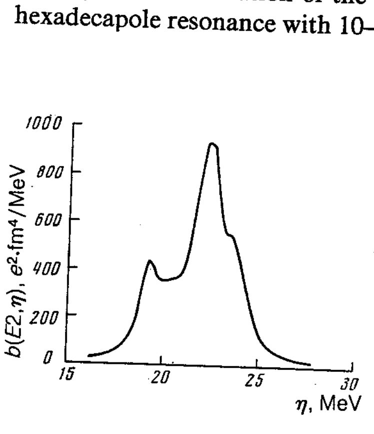

FIG. 2. Strength function for $E2$ transitions from the ground state to states of the isovector GQR in ^{208}Pb, calculated with $\Delta = 1$ MeV.

The isovector multipole resonances have been investigated more poorly experimentally. In ^{208}Pb, the isovector quadrupole resonance[2] lies at 21.5 MeV and has 80% EEWSR. Our calculations give $E_x = 21.9$ MeV and 81% EEWSR. The strength function for the isovector quadrupole resonance is shown in Fig. 2. We find that $\Gamma = 5$ MeV, which is in good agreement with the calculations performed within the framework of the theory of nuclear fields.[28] Very similar values for the energy and EEWSR were obtained in Ref. 25 with separable forces and exact allowance for the continuum. This demonstrates once again that the continuum can be approximated by quasi-discrete states in calculations of the characteristics of giant resonances of low multipolarity. It is interesting to note that the GQR characteristics calculated with separable forces are very close to those obtained by using the Landau–Migdal interaction. In Ref. 29, the GQR in ^{208}Pb was found to be concentrated at $E_x = 10.6$ MeV and had the integral strength $B(E2\downarrow) = 1010\ e^2\cdot$fm^4. QPM calculations yield $B(E2\downarrow) = 1029\ e^2\cdot$fm^4. The QPM is also successful in describing the energies and excitation probabilities of low-lying collective levels of ^{208}Pb (Ref. 18). The correct description of the integral characteristics of both low-lying levels and resonances suggests that a good description of the partial widths of γ decays to low-lying states will also be possible.

Having chosen the wave functions in the form of a superposition of one- and two-phonon states, we can calculate the reduced probabilities of electromagnetic transitions of multipolarity λ between these states:

$$B(\lambda, J_i \to J_f) = \frac{1}{2J_i+1} \sum_{\mu, M_i M_f} |\langle J_f M_f | M(\lambda\mu) | J_i M_i \rangle|^2. \quad (3)$$

Here $M(\lambda\mu)$ is the electromagnetic transition operator. If we represent the operator $M(\lambda\mu)$ in the second-quantized form and substitute in (3) the expression for the wave function of the initial (i) and final (f) states (1), we obtain the reduced probability in terms of the structure coefficients R and P of these states. The resulting expression is difficult to handle and we reproduce it here in schematic form:

$$\begin{aligned} B(\lambda, J_i \to J_f) \sim | & A_{11} R_{i_i}(J_i\nu_i)\, R_{i_f}(J_f\nu_f) \\ & + A_{21} R_{i_f}(J_f\nu_f)\, P^{\lambda i}_{J_f i_f}(J_i\nu_i) \\ & + A_{12} R_{i_i}(J_i\nu_i)\, P^{\lambda i}_{J_i i_i}(J_f\nu_f) \\ & + A_{22} P^{\lambda_i i_i i_i}_{\lambda_i' i_i'}(J_i\nu_i)\, P^{\lambda_i' i_i}_{\lambda_{f_2} i_{f_2}}(J_f\nu_f)|^2, \end{aligned} \quad (4)$$

where A_{ij} is a combination of phonon amplitudes and geometric composition factors for angular momenta. The first term in this expression describes the transition between the single-phonon components of the wave function of the initial and final states, the second describes the transition from the

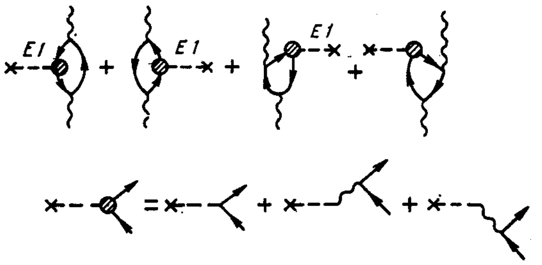

FIG. 3. Diagrammatic representation of the matrix elements for $E1$ decay of the isoscalar $E2$ resonance to the low-lying 3^- level.

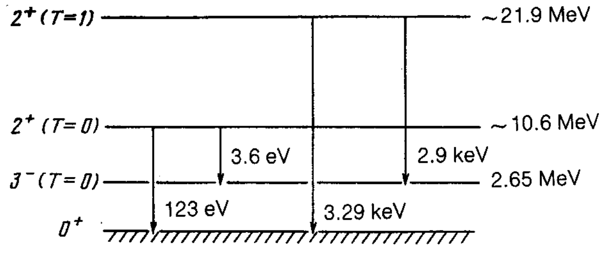

FIG. 4. γ decay of quadrupole resonances with $T = 0, 1$ in ^{208}Pb.

two-phonon component of the initial state to the single-phonon component of the final state, and so on. We shall consider γ transitions from the region of the giant resonance to low-lying states in which the two-phonon admixture is small, i.e., $P^{\lambda_{f_1 i_1} f_1}_{f_2 f_2} \sim 0$. In our problem, therefore, the quantity $B(E\lambda)$ is determined largely by the first two terms in (4).

These probabilities are directly related to the partial γ widths. For example, for $E1$ transitions, we have

$$\Gamma_{if}(E1, E_\gamma) = 1{,}05 E_\gamma^3 B(E1, J_i \to J_f) \text{ eV},$$

where $E_\gamma = E_i - E_f$ and is expressed in MeV, and $B(E1)$ is expressed in units of $e^2 \cdot \mathrm{fm}^2$. We have used these formulas to calculate the partial γ widths for the decay of the isoscalar and isovector quadrupole resonances in ^{208}Pb to a series of low-lying levels. Figure 3 shows the diagrams for the γ decays of the GDR.

The level energies and the γ-decay widths are shown in Fig. 4 for the isoscalar ($T = 0$) and isovector ($T = 1$) $E2$ resonances in ^{208}Pb. It is clear from this figure that the isoscalar $E2$ resonance has a very small width ($\Gamma = 3.6$ eV) for the decay to the first collective 3^- state. This has a simple explanation, as was noted in Refs. 29–31. Thus, the $E1$ transitions between collective isoscalar states are accompanied by destructive interference of the neutron and proton matrix elements that contribute to the width of this transition.

Moreover, the effective charge is reduced by the dipole polarizability of the core. When the dipole polarizability is taken into account, which in the QPM corresponds to excitation of two-phonon states that include the giant dipole resonance (GDR), it is found that the γ transitions obey the following rule: $E1$ transitions with energies greater than that of the dipole resonance are enhanced, whereas those with lower energy are weakened.[31] This is so because two-phonon states $[Q^+_{1i} Q^+_{\lambda\mu_i}]$ with 1^- phonons forming the GDR lie in the region $E_x > E_{\mathrm{GDR}}$. Because of the large $E1$ transition matrix element, there are strong transitions from these two-phonon components to the single-phonon component $Q^+_{\lambda\mu i}$ of the final state. The admixture of such two-phonon components in the wave function (1) is significant only for states with $E_x > E_{\mathrm{GDR}}$, and transitions to the final state from this energy range are determined by the first two terms in (4), whereas for states with lower energy, only the first term of (4) provides an appreciable contribution. The result of all this is that the γ transitions from the isovector resonance should be appreciably enhanced by the GDR admixture. Moreover, the $E1$ transitions between isoscalar and isovector single-phonon states are accompanied by an enhancement due to the coherent contribution of neutron and proton matrix elements. It is clear from Fig. 4 that the width of the $E1$ transition to the 3^-_1 level is practically the same as for the transition to the ground state. This width is found to be somewhat greater in other theoretical calculations.[29]

We have also calculated the decay widths for the isoscalar $E2$ and $E3$ resonances in ^{90}Zr. The overall picture is found to be similar to that for ^{208}Pb. In ^{90}Zr, we find that $\Gamma_\gamma = 2.1$ eV for the $E1$ transitions from the isoscalar GQR to the 3^-_1 level, and $\Gamma_\gamma = 0.5$ eV for the decay of the high-lying isoscalar octupole resonance. As in ^{208}Pb, the $E1$ transitions between the isoscalar states are appreciably suppressed for the reasons given above.

The enhancement of the $E1$ transitions from the isovector $E2$ resonance opens up new possibilities for its investigation in $(p, p'\gamma)$ and $(e, e'\gamma)$ reactions.

Let us now examine the decay of the isoscalar quadrupole resonance in greater detail. Our calculated ratio of the width of the γ decay to the ground state and the total width $\Gamma_{\gamma 0}/\Gamma_{\mathrm{tot}}$ is 4×10^{-5} for ^{208}Pb and 1.5×10^{-5} for ^{90}Zr. The values extracted from experimental spectra on the assumption of a 100% exhaustion of the sum rule are 8.62×10^{-5} and 4.6×10^{-5}, respectively. Since in our case we have 67% EEWSR in ^{208}Pb and 50% EEWSR in ^{90}Zr, whereas the experimental data are at present subject to 50–60% uncertainty, we may conclude that the theory is in agreement with experiment. However, it should be noted that the different EEWSR calculations lead to results that are similar to our own and, on the whole, reproduce quite well the hadron and light-on inelastic scattering data.

As we noted above, the region of the isoscalar GQR in ^{208}Pb contains a hexadecapole resonance from which there are again $E1$ transitions to the 3^-_1 level. Our value of the width for these transitions is $\Gamma_\gamma = 13$ eV. For transitions to the 5^-_3 level with excitation energy 4 MeV, the calculations give $\Gamma_\gamma(4^+ \to 5^-) = 60$ eV. If we take the γ-transition intensity from the isoscalar GQR to the ground state as our unit, then for transitions to the 3^-_1 level in ^{208}Pb our calculations give 0.03 for the relative intensity and 0.49 for the transition to the 5^-_3 level. The experimental values are 0.04 ± 0.04 and $0.025 - 0.5$, respectively. Of course, the precision of the experimental data will have to be increased and a more complete theoretical analysis will be necessary.

We can conclude from these calculations that studies of the decay properties of giant resonances provide new information about complex components of their wave functions, and appreciably extend the range of studies of the structure of high-lying collective states.

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