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GAMMA-DECAY OF GIANT RESONANCES

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The partial widths of the γ–decay of the giant E2 and E4 resonances in ^{90}Zr and ^{208}Pb to low–lying states are calculated within the quasiparticle–phonon model. The complex configurations of the wave function can be concluded to be rather important for correct description of the decay properties of highly excited nuclear states. It is shown that due to the core polarization the decay of the isovector resonances is more intensive compared to the isoscalar ones.

1. INTRODUCTION

A lot of information has been obtained on the properties of the giant resonances from the inelastic scattering studies using electrons and hadrons as probes[1–3]. The main mechanism of the giant resonances damping appears to be the excitation of low–lying surface vibrations induced by the interaction of the nuclear surface with the particle and hole of the resonance[4–9]. In the giant resonance studies the background subtraction is one of the main sources of uncertainties and no quantitative calculations of the shape and intensity of the background are available. A good peak–to–background ratio is crucial to a reliable giant resonance analysis when no exact estimation of the background is possible. The peak–to–background ratios obtained with intermediate energy heavy ions[4] as well as the differential cross sections are large allowing one to perform coincidence experiments to study the decay of the giant resonances with high counting rates. The study like that can give direct insight into the wave function of the giant resonances. These studies are carried out in the experiments where the γ–rays or light particles deexciting the resonance are detected in coincidence with inelastically scattered particles[2,3,11–13].

Recently, the experimental detection of the γ–decay of the giant quadrupole resonance (GQR) into the ground state in ^{208}Pb and ^{90}Zr has been reported[11–13]. In addition to the γ–decay into the ground state the branching ratios to the low–lying excited states have been measured as well. In general, electric dipole transitions are most likely to be observed experimentally. This fact restricts the multipolarity of the giant resonances which may be studied through γ–decay into the low–lying states with the given values for the angular momentum and parity.

2. FORMULAE AND NUMERICAL DETAILS

The aim of this paper is to calculate the partial widths of the γ–decay of the E2 and E4 giant resonances in ^{90}Zr and ^{208}Pb into low–lying states within the quasiparticle–phonon model (QPM)[14–16].

The model Hamiltonian includes the average field, superconducting pairing interactions and multipole–multipole forces with the Bohr–Mottelson radial dependence.

We take into account the coupling between the one–phonon and two–phonon components. Thus, the wave function of an excited state is

$$\Psi_\nu(JM) = \{\sum_i R_i(J\nu)Q^+_{JMi} + \sum_{\lambda i\, \lambda' i'} P^{\lambda' i'}_{\lambda i}(J\nu)\left[Q^+_{\lambda\mu i}Q^+_{\lambda'\mu' i'}\right]_{JM}\}\,\Psi_0 \qquad (1)$$

where Ψ_0 is the phonon vacuum, $Q^+_{\lambda\mu i}$ is the phonon creation operator and ν is the number of an excited state. The secular equation defining the energies $\eta_{J\nu}$ of the states and the quantities R, P are given in ref.[15]. For the investigation of highly excited states, it is reasonable to calculate the corresponding strength functions[16]. Let $\Phi_{J\nu}$ be the amplitude of the excitation on the state $\Psi_\nu(JM)$ in some nuclear reaction. Then, instead of the values $\mid \Phi_{J\nu} \mid^2$ for each state with the energy $\eta_{J\nu}$ we calculate the strength function

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

Δ is the averaging energy interval. It is worth mentioning that a strength function is essentially the same as a response function. For the numerical calculations we use the Saxon–Woods potential with the set of parameters from our previous paper[17]. The single–particle energy levels near the Fermi surface obtained with this set of parameters are close to the experimental values. The constants of the multipole forces have been determined from the experimental data on the energies and $B(E\lambda)$ values for the lowest states. The ratio of the isoscalar to the isovector constants has been fixed so as to describe the experimental position of the GDR. We have used the value $\Delta = 1.0\ MeV$. All calculations have been performed with the modified version of the code GIRES[18].

3. DISCUSSION

Before turning to the γ–decay of the giant resonances, we should be sure that the giant resonances are described correctly. We have calculated the integral characteristics of the E2 and E4 resonances in ^{208}Pb. To describe giant resonance damping we

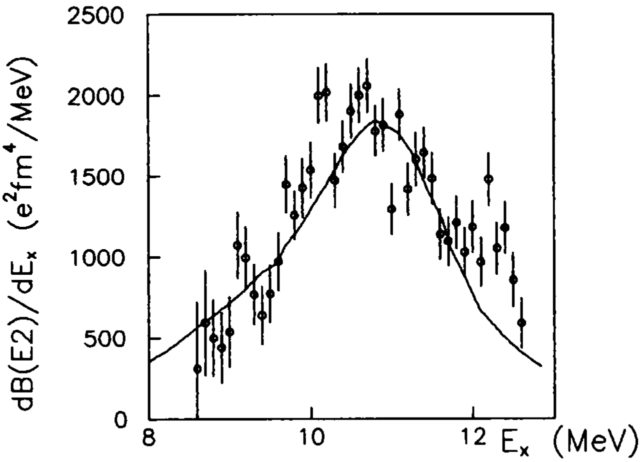

FIGURE 1

The strength function of the E2 transitions from the ground state to the states of the isoscalar GQR in ^{208}Pb (The solid curve represents the QPM calculations; the dots are the experimental data from the paper[19]).

use the excited state wave function as a mixture of one– and two–phonon states (see formula (1)).

The E2 nuclear response, as inferred from the $^{208}Pb(e,e'n)$ measurements[19], is compared to our calculation in fig.1. One can see a good agreement of the experimental data with the theoretical calculations. The results of our calculations for the energies, widths (Γ), energy weighted sum rule (EWSR) of the E2 and E4 resonances in ^{208}Pb and the experimental data are given in table 1. A value for the spreading width is obtained from the standard deviation of the strength function.

The isoscalar GQR in our calculations is located around $E_x = 10.6\ MeV$ with the $B(E2\downarrow) = 1029\ e^2fm^4$ which practically coincide with the results of ref.[20,21]. The isoscalar EWSR is exhausted by 67%. The isoscalar E4 resonance is located

TABLE 1

The integral characteristics of the E2 and E4 resonances in ^{208}Pb.

	Experiment			Theory		
J^π	E_x, MeV	Γ, MeV	EWSR, %	E_x, MeV	Γ, MeV	EWSR, %
2^+	10.5÷10.9	2.4÷3.0	60÷80	10.6	3.1	67
4^+	~10.9	~4.0	10÷30	10.9	3.2	16

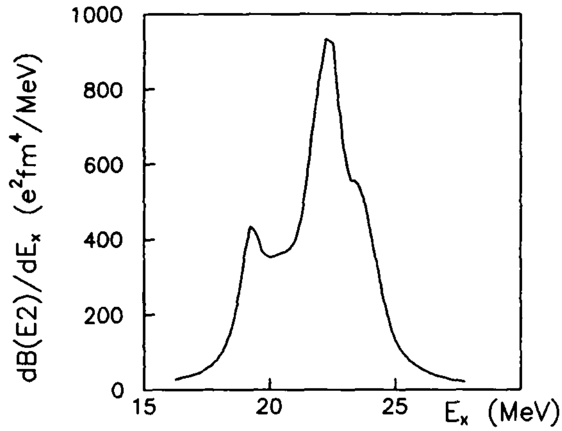

FIGURE 2

The strength function of the E2 transitions from the ground state to the states of the isovector GQR in ^{208}Pb.

in the same energy interval and the EWSR is exhausted by 10–30%[2]. For the E4 resonance we get $E_x = 10.9\ MeV$, $\Gamma = 3.2\ MeV$ and EWSR is exhausted by 16%. The calculated isovector E2 strength function is shown in fig.2. For the isovector E2 quadrupole resonance we get $E_x = 21.9\ MeV$, $\Gamma = 5\ MeV$ and the EWSR is exhausted by 81%. The experiment[2] gives $E_x = 21.5\ MeV$ and the EWSR is exhausted by 80%.

Using the wave functions (1) for the initial and final states one can estimate the reduced $E\lambda$ or $M\lambda$ transition probability

$$B(\lambda, J_i \to J_f) = \frac{1}{2J_i+1} \sum_{\mu, M_i, M_f} |< J_f M_f \mid \mathcal{M}(\lambda\mu) \mid J_i M_i >|^2 \ . \tag{3}$$

Here $\mathcal{M}(\lambda\mu)$ is the electromagnetic transition operator. As the total expression for the $B(\lambda, J_i \to J_f)$ is rather cumbersome, we give its schematic representation

$$\begin{aligned} B(\lambda, J_i \to J_f) \ \sim\ & \Big| \mathcal{A}_{11} R_{i_i}(J_i\nu_i) R_{i_f}(J_f\nu_f) + \mathcal{A}_{21} R_{i_f}(J_f\nu_f) P^{\lambda i}_{J_f i_f}(J_i\nu_i) \\ + \ & \mathcal{A}_{12} R_{i_i}(J_i\nu_i) P^{\lambda i}_{J_i i_i}(J_f\nu_f) + \mathcal{A}_{22} P^{\lambda_{i1} i_{i1}}_{\lambda_i i_i}(J_i\nu_i) P^{\lambda_i i_i}_{\lambda_{f2} i_{f2}}(J_f\nu_f) \Big|^2 \end{aligned} \tag{4}$$

where $\mathcal{A}_{ij}$ are some combination of the phonon amplitudes and geometrical factors.

There is a simple relation between the reduced probability and the partial γ–decay width

$$\Gamma_{ij}(E1, E_\gamma) = 1.05 \cdot E_\gamma^3 \cdot B(E1, J_i \to J_f)\, eV$$

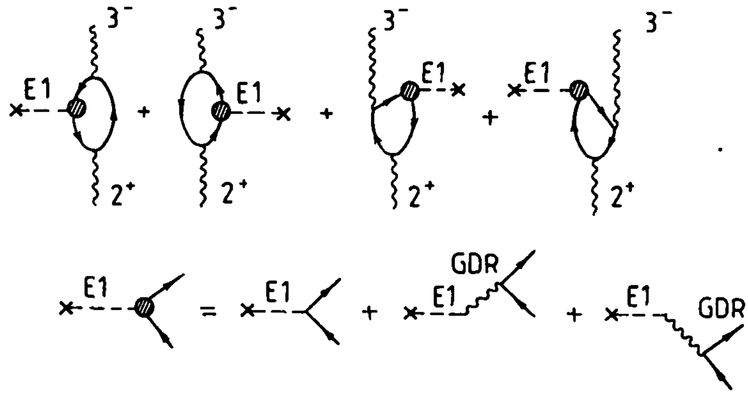

FIGURE 3

Diagrammatic representation of the E1 γ–decay matrix elements of the isoscalar E2 resonance to the low–lying 3^- state.

where $E_\gamma = E_i - E_f$ is the γ– transition energy in MeV and $B(E1)$ is in the units e^2fm^2. Using the formulae mentioned above we have calculated the partial widths of the γ–decay of the GQR into the ground and low–lying excited states in ^{208}Pb and ^{90}Zr. The first two terms of expression (4) are dominating for the γ–decay widths of the GQR. The lowest order diagrams describing the γ–decay of the GQR into the low–lying vibration states are shown in fig.3.

The results for the γ–decay of the isoscalar GQR at $E_x \approx 10.6\ MeV$ and the isovector GQR at $E_x \approx 21.9\ MeV$ into the ground state and the first excited 3^- state are shown in fig.4. The decay width of the isoscalar GQR into the 3^-_1 is very small. Due to the isovector nature of the E1–operator the neutron and proton amplitudes tend to cancel when the states have predominantly isoscalar character[21–23]. This is the case for the isoscalar GQR and the low–lying 3^- states.

Furthermore, a marked quenching of the transitions is observed which arises from the coupling to the GDR[21–23]. The effective charge decreases due to the dipole core polarization corresponding to the excitation of two–phonon states, one of which is 1^- phonon of the GDR. For the states below the GDR the E1 effective charge becomes very small, while for the transitions having similar or larger energies than the GDR the situation is reverse. As a result, the γ–decay of the isovector resonances must be strongly enhanced due to the coupling to the GDR. The enhancement of the E1 transitions between isovector and isoscalar states is caused by the coherent interference of neutron and proton matrix elements.The decay width of the E1–transition from

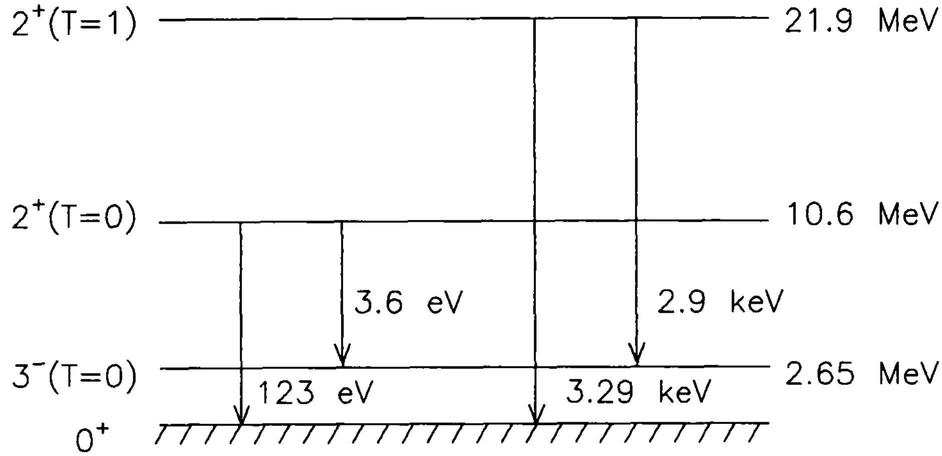

FIGURE 4

γ-decay of the quadrupole resonances in ^{208}Pb.

the isovector E2 resonance into the 3_1^- state is practically the same compared to the transition into the ground state, as is seen from fig.4. The calculations within other theoretical approaches[21] get the value for this width even larger than we have.

A few interesting examples for the relative γ-branching to the low-lying states in ^{208}Pb from the isoscalar GQR are summarized in table 2.

We have also calculated the decay widths of the isoscalar E2 and E3 resonances in ^{90}Zr. The results for ^{90}Zr give a picture qualitatively alike with ^{208}Pb. In ^{90}Zr we get $\Gamma_\gamma = 2.1\ eV$ for the E1-transition from the isoscalar GQR to the 3_1^- state and $\Gamma_\gamma = 0.5\ eV$ for the decay of the high-lying octupole resonance. The E1-transitions between the isoscalar states are quenched as in ^{208}Pb.

TABLE 2

Relative γ-branching to low-lying states in ^{208}Pb.

Final state	Final state	Decay branch relative to g.s.	
energy	spin	Experiment	Theory
0.0	0^+	1.0	1.0
2.61	3_1^-	0.04±0.04	0.03
4.085	2^+	$0.02^{+0.05}_{-0.02}$	0.0093
4.97	3^-	1.8±0.5	1.6
5-7	1^-	1.15±0.5	0.49

The enhancement of the E1–transitions from the isovector E2 resonance opens new possibilities to investigate the properties of this resonance via the (p,p'γ) and (e,e'γ) reactions.

Consider in detail the decay of the isoscalar quadrupole resonance. The ratio of the γ–decay into the ground state width to the total width $\Gamma_{\gamma 0}/\Gamma_{tot}$ in our calculations is $4 \cdot 10^{-5}$ for ^{208}Pb and $1.5 \cdot 10^{-5}$ for ^{90}Zr. These values, extracted from the experimental spectra assuming that the EWSR are exhausted by 100%, are equal to $8.62 \cdot 10^{-5}$ and $4.6 \cdot 10^{-5}$, respectively. Taking into account that for the isoscalar quadrupole resonance in our calculations the EWSR is exhausted by 67% in ^{208}Pb and 50% in ^{90}Zr and experimental data have uncertainties about 50–60%, the theory is in agreement with the experiment. We have to point out that different theoretical approaches give close values of the EWSR and reproduce well, in general, the experimental values extracted from the inelastic electron, hadron and light ion scattering data.

As has been mentioned earlier, the hexadecapole resonance in ^{208}Pb, which decays by the E1–transitions into the 3_1^- state, is located in the same energy range as the isoscalar GQR and we obtain for this decay the width $\Gamma_\gamma = 13\ eV$. For the transitions to the 5_3^- level at $E_x = 4\ MeV$ we get the value $\Gamma_\gamma(4^+ \rightarrow 5_3^-) = 60\ eV$. Thus, the ratios of γ–transitions from the isoscalar E2 and E4 resonances on the 3_1^- state and on the 5_3^- state to the γ–transitions from the isoscalar E2 on the ground state are 0.03 and 0.49, while the experimental values are 0.04 ± 0.04 and $0.025 \div 0.5$, respectively.

4. CONCLUSIONS

Our calculations show that due to the core polarization the γ–decay of the isovector resonance is more intensive compared to the isoscalar ones. It can be concluded that the complex configurations of the wave functions are rather important for a correct description of the decay properties of giant resonances. By this reason one can obtain new information concerning complex configurations in the wave functions of high–lying collective states.

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