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The influence of the GDR on the low-energy E1 transitions in spherical nuclei *

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Low-energy El-transitions in spherical nuclei forbidden in the ideal boson picture are considered. For that the internal fermion structure of nuclear excitations is taken into account. Several examples of such transitions calculated within the Quasiparticle Phonon Model are considered and the role of dipole core polarization is discussed.

1. Introduction

Recently, the theoretical study of low-lying 1^- excited states is stimulated by the new, very precise experimental data around closed N=82 and Z=50 shells [1]. It is shown [2,3], that first 1^- state is member of the two-phonon quadrupole-octupole multiplet. The two-phonon quadrupole-octupole states are isoscalar in origin and the corresponding B(E1) values should be the result of a delicate interplay between isoscalar and isovector modes in the structure of the low-lying excited states. Direct excitation of two-phonon states from the ground state by the electromagnetic field is possible only due to the internal fermion structure of phonons [2] but it is strongly hindered as compared to the excitation of one-phonon states. It is confirmed by the systematics [4] that the B(E1) value varies from 10^{-4} to 10^{-6} W.u. for low-energy El-transitions. The microscopic studies of these hindered low-energy El-transitions are of great interest because they allow us to look inside the fermion structure of nuclear vibrations leading to the boson forbidden transitions [5]. A study carried out within the Quasiparticle Phonon Model (QPM) [6] will be summarized in the present paper.

2. Theoretical treatment of low-energy El-transitions

Let us follow the so-called boson mapping procedure and introduce a phonon creation operator $Q^+_{\lambda\mu i}$ for the one-phonon state as a superposition of a bi-linear forms of the quasiparticle creation α^+_{jm} and annihilation α_{jm} operators

$$Q^+_{\lambda\mu i} = \frac{1}{2}\sum_{\tau}^{n,p}\sum_{jj'}\left\{\psi^{\lambda i}_{jj'}[\alpha^+_j\alpha^+_{j'}]_{\lambda\mu} - (-1)^{\lambda-\mu}\varphi^{\lambda i}_{jj'}[\alpha_{j'}\alpha_j]_{\lambda-\mu}\right\} \; ; \quad (1)$$

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the amplitudes $\psi_{jj'}^{\lambda i}$ and $\varphi_{jj'}^{\lambda i}$ as well as the phonons energies are obtained by solving RPA equations.

The main advantage of the QPM is that making use of a separable form of the residual interaction it allows easily to go beyond the one-phonon approximation and take into account a coupling between one- and multi-phonon configurations. The boson mapping gives rise to two main problems. The first is an admixture of spurious states which violate the Pauli principle. The second is related to the fact that the set of pure n-phonon states is mathematically non-orthonormal. To avoid these problems we introduce an orthonormal set of excited states with angular momentum J and projection M in even-even nuclei as a mixture of one-, two-, and three-phonon configurations:

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

$$+ \sum_{\substack{\lambda_1 i_1 \lambda_2 i_2\\ \lambda_3 i_3 I}} T^{\lambda_1 i_1 \lambda_2 i_2 I}_{\lambda_3 i_3}(J\nu) \left[\left[Q^+_{\lambda_1\mu_1 i_1} \times Q^+_{\lambda_2\mu_2 i_2} \right]_{IK} \times Q^+_{\lambda_3\mu_3 i_3} \right]_{JM} \Bigg\} \Psi_0 \tag{2}$$

and use the internal fermion structure of phonons in calculation of the norm of the wave function (2). This means that the exact commutation relations between phonon operators and exact commutation relations between phonon and quasiparticle operators are applied. The model Hamiltonian is then diagonalized on the set of wave functions (2) to obtain the energy spectra and structure coefficients R, P and T.

The electric transition operator written in terms of quasiparticle and phonon operators has the form:

$$M(\mathrm{E}\lambda\mu) = \sum_\tau^{n,p} e_\tau^{(\lambda)} \sum_{jj'} \frac{< j||\mathrm{E}\lambda||j' >}{\sqrt{2\lambda+1}} \Bigg\{ \frac{u_{jj'}^{(+)}}{2} \sum_i (\psi_{jj'}^{\lambda i} + \varphi_{jj'}^{\lambda i})$$

$$\times (Q^+_{\lambda\mu i} + (-)^{\lambda-\mu} Q_{\lambda-\mu i}) + v_{jj'}^{(-)} [\alpha_j^+ \alpha_{j'}]_{\lambda\mu} \Bigg\} \ . \tag{3}$$

where $< j||\mathrm{E}\lambda||j' > \equiv < j||i^\lambda Y_\lambda r^\lambda||j' >$ is a reduced 1p1h transition matrix element, $e_\tau^{(\lambda)}$ are effective charges for neutrons and protons and $u_{jj'}^{(+)}, v_{jj'}^{(-)}$ are combination of Bogoliubov coefficients. The first term of Eq. (3) corresponds to one-phonon exchange between initial and final states and only transitions described by this term are allowed when phonons are treated as ideal bosons. The second term in Eq. (3) allows Eλ-transitions (boson forbidden transitions) between configurations with the same number of phonons or between the ones which differ by an even number of phonons. Examples of such transitions are given in ref. [5].

3. Analysis of some low-energy E1-transitions

We have calculated some of these "forbidden" E1-transitions in ^{120}Sn, ^{144}Nd and ^{144}Sm for which experimental data are available. It was proposed [7] that the lowest 1^- state

Table 1
Excitation energies and B(E1) values for first 1^- states in ^{120}Sn, ^{144}Sm and ^{144}Nd.

	E_x, MeV		Main two-phonon configuration, %	$B(E1, 0^+_{g.s.} \to [2^+_1 \otimes 3^-_1]_{1^-})$, $10^{-3}\ e^2 fm^2$			
	Theory	Exp.		Theory			Exp.
				main	*polar.*	*total*	
^{120}Sn	3.29	3.271	94	12.2	2.1	7.2	7.6
^{144}Sm	3.44	3.225	95	52.2	8.8	18.1	18.9
^{144}Nd	2.57	2.185	82	51.6	21.8	6.3	7.2

was a member of the two-phonon multiplet $[2^+_1 \otimes 3^-_1]$. Comparing the values of the E2-transitions $2^+_1 \to 0^+_{g.s.}$ and $1^-_1 \to 3^-_1$ the experimental evidence of two-phonon nature of the lowest 1^- has been achieved [8]. Theoretically, the properties of the low-lying 1^- states and especially the E1-transitions have been studied in the framework of different nuclear models. Considering the lowest 1^- state as a pure two-phonon one, the theoretical calculations overpredicted the B(E1) value for this state. To improve the situation it was suggested [9] that renormalized values of effective charges for E1-transitions should be used. This takes phenomenologically into account a core polarization due to the coupling of the first 1^- state to GDR. The renormalized effective charge was estimated in a static limit [10] for heavy nuclei. In our approach we are able to avoid the use of effective charge by including explicitly the GDR phonons into the model wave function of Eq. (2).

The results of our calculations of the excitation energies and the B(E1) values for the lowest 1^- states along selected nuclei are presented in Table 1 in comparison with experimental data. In the column *main* of Table 1 the B(E1) value for the transition to the two-phonon component $[2^+_1 \otimes 3^-_1]_{1^-}$ of the wave function (2) of the first 1^- state is presented. The inclusion of the GDR phonons in the model wave function improves the agreement. Since GDR is located more than 10 MeV higher, its admixture to the lowest 1^- state is very weak (less than 0.5% in the present calculation). But the large value of the collective one-phonon exchange matrix element $< \mathrm{GDR}|M(\mathrm{E1})|0^+_{g.s.} >$ leads to the fact that the contribution of GDR and those of two-phonon term are the values of the same order of magnitude. The last value, core polarization effect, is presented in the column *polar.* of Table 1. When the interference effect between the transitions to two- and one-phonon components of this state wave function is taken into account, we obtain the final result given in the column *total*. For the lowest 1^- state the interference has a destructive character and brings the final result in good agreement with experimental findings.

The first 1^- state may decay by E1-transition not only into the ground state but also into the 2^+_1 state . The results of our calculation for the second transitions are presented in Table 2. The GDR core polarization is marginal for the $B(E1; [2^+_1 \otimes 3^-_1]_{1^-} \to 2^+_1)$ value. The reason is that the admixture of the two-phonon $[\mathrm{GDR} \otimes 2^+_1]_{1^-}$ configuration in the wave function of the lowest 1^- state is much weaker as compared to the admixture of the GDR itself in the wave function of this state. Similar arguments for the GDR core polarization are also valid for the E1-decay of the $[3^-_1 \otimes 3^-_1]_{2^+,4^+}$ states into the 3^-_1 state.

The GDR core polarization may play an important role for E1-transitions between two

Table 2
B(E1) values for some E1-transitions between excited states in ^{120}Sn, ^{144}Sm and ^{144}Nd.

	B(E1, $J_i \to J_f$), 10^{-3} e^2fm^2							
	$[2_1^+ \otimes 3_1^-]_{1^-} \to 2_1^+$		$[3_1^- \otimes 3_1^-]_{2^+} \to 3_1^-$		$3_1^- \to 2_1^+$			
	Theory	Exp.	Theory	Exp.	Theory			Exp.
					main	*polar.*	*total*	
^{120}Sn	0.08	–	0.93	–	3.7	0.34	1.8	2.02
^{144}Sm	0.76	0.61	1.71	1.20	24	6.2	5.9	5.0
^{144}Nd	3.4	4.25	0.52	–	13.5	3.36	3.38	1.77

excited states with the main one-phonon configurations. An example of such a transition is the decay of the 3_1^- state into the 2_1^+ state. As for the decay of the $[2_1^+ \otimes 3_1^-]_{1^-}$ state into the ground state, we have for this transition a competition between weak "forbidden" $< 2_1^+|E1|3_1^- >$ matrix element, and two collective $< [GDR \otimes 3_1^-]_{2^+}|E1|3_1^- >$ and $< 2_1^+|E1|[GDR \otimes 2_1^+]_{3^-} >$ matrix elements with small weighting factors. The results of our calculations of the $3_1^- \to 2_1^+$ decay are presented in Table 2. Separate contributions of transitions between one-phonon components of the 3_1^- and 2_1^+ states and between one- and two-phonon configurations, [GDR$\otimes$low-lying state], are shown in columns *main* and *polar.*, respectively.

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