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MAGNETIC POLARIZATION AND TWO-PHONON STATES

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1 Introduction

A large body of precision experimental data on decay properties of nuclear states up to excitation energies 3-4 MeV has been collected during the last years due to the great progress in the γ- ray detection techniques. Obviously, the structure of nuclear excited states at these energies is more complicated than that of the lowest ones which are mainly of two-quasiparticle or one-phonon character. Thus, the properties of the multi-quasiparticle and multi-phonon states appear to be the main goal of many experiments. Among them the main achievements concern the lowest E1 states in some spherical nuclei [1]. These states are members of a two-phonon $[2_1^+ \otimes 3_1^-]$ quintet [1]. Their distinctive feature is the unexpectedly high excitation transition probability (~3 mW.u.). According to some theoretical studies [2, 3], at least one of the reasons for the large $B(E1, 0^+_{g.s.} \rightarrow 1_1^-)$ values is the coupling of a two-phonon state with the giant dipole resonance or, in other words, the dipole electric polarization of the nucleus. In the present paper we would like to focus our attention on the $J^\pi = 2^-$ member of the two-phonon quintet with unnatural parity.

We argue that some properties of the two-phonon 2^- state are also strongly affected by the core polarization (of magnetic type in this case). The reason is analogous to the electric dipole two-phonon state – the coupling with high-lying spin-dipole resonances. Due to the latter, a strong reduction of M2-transition rates between low-lying states in some odd mass spherical nuclei has been established [4-6]. Here, we study the role of this effect on the two-phonon 2^- state in the even-even nuclei ^{142}Ce and ^{144}Sm. Special interest in the present case is that the two-phonon unnatural parity states are combined by natural parity excitations - isoscalar quadrupole and octupole vibrational quanta (phonons). So we deal with the magnetic polarization effect for predominantly electric states.

[1] The notation $[2_1^+ \otimes 3_1^-]$ stands for the coupling of the 2_1^+ and 3_1^- RPA phonon states.

2 Theory

Energies and γ- decay properties of the two-phonon states are calculated in the framework of the extended version of the quasiparticle-phonon model (QPM) [7]. This version in its most complete form has already been used to analyze the two-phonon states in spherical nuclei of the chains of isotones with N= 82, 84 in [2, 8].

The QPM Hamiltonian includes neutron and proton mean fields, the BCS pairing interactions and particle-hole separable multipole and spin-multipole interactions. Moreover multipole pairing interactions in the particle-particle channel with multipolarities $\lambda = 2, 3$ are taken into account as well.

Building blocks to construct the model configuration basis are the quasiparticle RPA (QRPA) phonons defined as follows:

$$Q^+_{\lambda\mu i}\Psi_0 = \frac{1}{2}\sum_{j_1 j_2}\left(\psi^{\lambda i}_{j_1 j_2}\left[\alpha^+_{j_1 m_1}\alpha^+_{j_2 m_2}\right]_{\lambda\mu} - (-1)^{\lambda-\mu}\phi^{\lambda i}_{j_1 j_2}\left[\alpha_{j_2 m_2}\alpha_{j_1 m_1}\right]_{\lambda -\mu}\right)\Psi_0 \qquad (1)$$

where α^+_{jm} and α_{jm} are the Bogoliubov quasiparticle creation and annihilation operators, Ψ_0 is the QRPA vacuum state which is supposed to be a ground state of an even-even nucleus and ψ and ϕ are the RPA forward and backward amplitudes, respectively. The notation $[\ldots]_{\lambda\mu}$ stands for angular momentum coupling. After a series of transformations the QPM Hamiltonian for an even-even nucleus is expressed in terms of the QRPA phonons only

$$H_{QPM} = \sum_{\lambda\mu i}\omega_{\lambda i}Q^+_{\lambda\mu i}Q_{\lambda\mu i} + \frac{1}{2}\sum_{\substack{\lambda_1\lambda_2\lambda \\ i_1 i_2 i}} U^{\lambda_2 i_2}_{\lambda_1 i_1}(\lambda i)\left[\left[Q^+_{\lambda_1\mu_1 i_1}Q^+_{\lambda_2\mu_2 i_2}\right]_{\lambda\mu} Q_{\lambda-\mu i}\right] + \qquad (2)$$
$$+(-1)^{\lambda-\mu}V^{\lambda_2 i_2}_{\lambda_1 i_1}(\lambda i)\left[\left[Q^+_{\lambda_1\mu_1 i_1}Q^+_{\lambda_2\mu_2 i_2}\right]_{\lambda\mu} Q^+_{\lambda-\mu i}\right] + h.c.$$

We denote by $\omega_{\lambda i}$ the energies of the QRPA phonons. Knowing the QPM Hamiltonian parameters one can calculate $\omega_{\lambda i}$ and the amplitudes ψ and ϕ from the QRPA equations and then the coupling matrix elements $U^{\lambda_2 i_2}_{\lambda_1 i_1}(\lambda i)$ and $V^{\lambda_2 i_2}_{\lambda_1 i_1}(\lambda i)$. Expressions for the latter can be found in [7].

To describe two-phonon states of an even-even nucleus, the following model wave function was used in [2, 8]:

$$\Psi_\nu(JM) = \left\{\sum_i R_i(J\nu)Q^+_{JMi} + \sum_{\substack{\lambda_1 i_1 \\ \lambda_2 i_2}} P^{\lambda_1 i_1}_{\lambda_2 i_2}(J\nu)\left[Q^+_{\lambda_1\mu_1 i_1}Q^+_{\lambda_2\mu_2 i_2}\right]_{JM} + \right.$$
$$\left. + \sum_{\substack{\lambda_1 i_1 \lambda_2 i_2 \\ \lambda_3 i_3 I}} T^{\lambda_1 i_1 \lambda_2 i_2 I}_{\lambda_3 i_3}(J\nu)\left[\left[Q^+_{\lambda_1\mu_1 i_1}Q^+_{\lambda_2\mu_2 i_2}\right]_{IK} Q^+_{\lambda_3\mu_3 i_3}\right]_{JM}\right\}\Psi_0 \qquad (3)$$

The system of equations for the unknown coefficients R, P, T and the energy of the state (3) was evaluated by a variational principle. The violation of the Pauli principle in the multiphonon components of (3) was minimized with the procedure given in [9, 10]. Note that for the trial wave function (3) the last term of the QPM Hamiltonian (2) (the term $\sim V$) vanishes.

3 Results and discussion

Here we discuss the lowest 2^- states in the nuclei ^{144}Sm and ^{142}Ce. Experimental data on low-lying 2^- states exist in refs. [12, 11]; moreover γ - decay properties of the two-phonon states in these nuclei have been studied within the QPM [2, 8]. We use mainly the results of the last two papers. Specifically, we use the same sets of model parameters (except constants of the spin-dipole interaction which will be discussed below).

The magnetic core polarization effect manifests itself through the B(M2, $2^- \to 0^+_{g.s.}$) value. Within the current approximation scheme the two terms of the magnetic quadrupole operator, which is supposed to be a one-body operator, contribute to the transition matrix element. The first one is proportional to the product of the one-phonon amplitude $R_i(J\nu)$ multiplied by the sum of ψ and ϕ amplitudes of the 2^-_i phonon. The second term is proportional to the two-phonon amplitude $P^{\lambda_1 i_1}_{\lambda_2 i_2}(2^-\nu)$ multiplied by $\psi^{\lambda_1 i_1}\phi^{\lambda_2 i_2}$. Of course, the summation over the corresponding phonon and single - particle quantum numbers is implied in both the cases. For the state of predominantly two-phonon structure just the first term describes the core polarization. It vanishes in the harmonic phonon picture when the 2_1^- state is pure $[2_1^+ \otimes 3_1^-]$. The importance of the last item for a two-phonon state was first pointed out in ref. [13].

Energies, wave function compositions, reduced probabilities of M2-decay of the first 2^--states in ^{142}Ce and ^{144}Sm are shown in Table 1. At a chosen values of model parameters the wave functions of the 2^--states are dominated by the two phonon $[2_1^+ \otimes 3_1^-]$ component. The overall contribution of the 2^- one-phonon components to every wave function is only of few per cent [2]. Nevertheless, the one-phonon components give the main contribution to the calculated B(M2, $2^- \rightarrow 0^+_{g.s.}$). The direct decay through two-phonon components makes up only a few percents of B(M2)$\downarrow$ (see Table 2). Let us remember that the decay through two-phonon components makes up 20-50% of the total transition rate to the ground state of the 1_1^- member of the two-phonon quintet $[2_1^+ \otimes 3_1^-]$ [2, 3, 8]. We attribute this difference to that spin-flip two-quasiparticle components, which play a negligible role in the structure of the isoscalar electric 2_1^+ and 3_1^- phonons, but contribute strongly to the B(M2).

It seems instructive to analyze what kind of the numerous QRPA 2^- phonons affect B(M2, $2^- \rightarrow 0^+_{g.s.}$) stronger. The QRPA calculations of M2-resonances with separable spin-multipole forces [14, 15] have shown two maxima of the $M2$-strength in a spectrum of a spherical nucleus. The first (lower) peak is at $E_x \sim 7-11$ MeV while the second (higher) one is at $E_x \sim 17$ MeV. The structures of the 2^- phonons in these two regions are quite different. The lower M2-resonance is formed by several strong M2-phonons. A sizable contribution to their excitation probabilities is given by the orbital part of the nuclear electromagnetic current. Moreover, the proton and the neutron wave function components of these states are in phase, i.e. these states are of the isoscalar nature [15].

[2]The minor differences with the results of refs. [2, 8] are due to the other values of spin-dipole coupling constants

Table 1

Energies, wave functions and B(M2; $2_1^- \rightarrow 0^+_{g.s.}$) values of the first 2^- states in ^{142}Ce and ^{144}Sm for $\kappa_1^{(12)} = \kappa_1^{(1)}$

Nucleus	Energy, MeV	Wave function (3)			B(M2; $2_1^- \rightarrow 0^+_{g.s.}$), μ_N^2fm^2	
		R, %	P, %	T, %	$g_s^{eff} = g_s^{bare}$	$g_s^{eff} = 0.6 g_s^{bare}$
^{142}Ce	2.67	1.1	71.5	24.0	6.2	2.7
^{144}Sm	3.54	3.6	96.4	< 1.0	25.3	12.1

Table 2

Contributions of different parts of 2_1^- state wave function to B(M2; $2_1^- \rightarrow 0^+_{g.s.}$) in ^{142}Ce and ^{144}Sm for different values of isovector spin-dipole constant $\kappa_1^{(12)}$ and $g_s^{eff} = g_s^{bare}$

Components of wave function (3)	B(M2; $2_1^- \rightarrow 0^+_{g.s.}$), μ_N^2fm^2			
	^{142}Ce		^{144}Sm	
	$\kappa_1^{(12)} = \kappa_1^{(1)}$	$\kappa_1^{(12)} = 0.5\kappa_1^{(1)}$	$\kappa_1^{(12)} = \kappa_1^{(1)}$	$\kappa_1^{(12)} = 0.5\kappa_1^{(1)}$
one+two phonon components	6.2	8.7	25.3	130
one-phonon components only	7.0	9.7	18.0	116
two-phonon components only	0.02	0.02	0.6	0.4

The high-lying maximum is due to a single strongly collective one-phonon state. Its wave function is composed by the spin-flip two - quasiparticle (practically, particle-hole) components with opposite signs of proton and neutron amplitudes (i.e. this is an isovector state). Our calculations show that the largest part of the core polarization effect for the 2^--states is due to the coupling with the lower M2-resonance. The main reason for this is a relatively strong interaction of the $[2_1^+ \otimes 3_1^-]$ configuration with these one-phonon 2^--states. The corresponding interaction matrix element $U_{3^-1}^{2^+1}(2^-i)$ is of an order of ~0.2-0.5 MeV, whereas for the high-lying M2-resonance it appears to be 5-10 times smaller. Moreover, the excitation energy of the latter is much higher. As a result, the high-lying M2-resonance contributes less than 5% to the total B(M2, $2^- \to 0^+_{g.s.}$) value. The difference in the coupling strength of the $[2_1^+ \otimes 3_1^-]$ configuration with low-energy and high-energy M2-resonances can be explained by the difference of one-phonon wave function compositions discussed above. It seems reasonable that the isovector spin-flip state weakly couples with the two-phonon state composed of the two electric isoscalar phonons. Note that the effect of the high-lying M2-resonance on M2-transition rates between low-lying states in odd-mass spherical nuclei is much more prominent [5, 6].

Of course, B(M2)- values showed in Tables 1 and 2 are dependent on the model parameters. They have been fixed in each nucleus to fit experimental data on the excited states of the simplest structures (the lowest vibrational states, giant resonances etc.) and cannot be varied strongly. An exception are the constants of spin-multipole interactions and effective gyromagnetic factors g_s^{eff}, g_l^{eff}, because data on spin-flip states are scarce.

Let us first discuss the role of the coupling constants $\kappa_0^{(12)}$, $\kappa_1^{(12)}$ of isoscalar and isovector spin-dipole interactions. Their values were discussed in more detail in ref. [15] (see also [5, 6]). It was shown that for schematic separable forces the following estimations were valid: $\kappa_1^{(12)} \approx \kappa_1^{(1)}$; $\kappa_0^{(12)} \simeq 0.1\kappa_1^{(12)}$ [3]. The isovector dipole constant $\kappa_1^{(1)}$ is fixed to reproduce the experimental energy of the E1 giant resonance. Just the above values of $\kappa_{0,1}^{(12)}$ are used in the present calculations (in refs. [2, 8] the isovector spin-dipole interaction was taken noticeably stronger). We study the dependence of B(M2, $2^- \to 0^+_{g.s.}$) on $\kappa_{0,1}^{(12)}$. The isoscalar spin-dipole interaction influences B(M2) - values weakly. A role of the isovector spin-dipole term is more important, especially in ^{144}Sm. In Table 2, one finds the values of B(M2)$\downarrow$ calculated at $\kappa_1^{(12)} = 0.5\kappa_1^{(1)}$. These values are noticeably larger than those calculated at $\kappa_1^{(12)} = \kappa_1^{(1)}$. This result can be explained in the following way. When the absolute value of $\kappa_1^{(12)}$ decreases the B(M2) strength shared between numerous 2^- phonons is pushed down to lower excitation energies and its increasing part concentrates in the region of the lower peak. Since these 2^- phonons are coupled with the $[2_1^+ \otimes 3_1^-]$ configuration stronger than the higher ones, the one phonon part of B(M2, $2^- \to 0^+_{g.s.}$) increases. The effect takes place in both the nuclei but it appears to be much stronger in ^{144}Sm than in ^{142}Ce. This is due to a specific feature of the 2^- excitations in ^{144}Sm. Since this nucleus is a semimagic one, its quadrupole - octupole two-phonon state has quite a high unperturbed energy and is very close to the lowest one-phonon 2^- state (the energy difference is around 50 keV). This lowest 2^- one-phonon state is almost a pure proton two-quasiparticle state $[1g_{7/2}1h_{11/2}]_Z$ with a relatively large B(M2)$\downarrow$ value. With decrease in $|\kappa_1^{(12)}|$ the two states mix stronger. At $\kappa_1^{(12)} = 0.5\kappa_1^{(1)}$ the one-phonon component contributes around 40% to the norm of the 2_1^- state in ^{144}Sm. With further weakening of the isovector spin-dipole interaction the first 2^- state in ^{144}Sm becomes predominately of the one-phonon structure and the second 2^- state becomes of the two-phonon quadrupole - octupole one. Moreover, the B(M2)$\downarrow$ value of the lowest QRPA 2^- state increases with a decrease in $|\kappa_1^{(12)}|$, thus enhancing additionally the B(M2, $2_1^- \to 0^+_{g.s.}$) value. The two-phonon 2_1^- state in ^{142}Ce is well separated in energy from the one-phonon 2^- states, and the one-phonon term of its wave function is influenced slightly by the isovector spin-dipole force. In this sense, the dependence of the B(M2, $2_1^- \to 0^+_{g.s.}$) on $\kappa_1^{(12)}$ in ^{142}Ce really reflects the effect of the magnetic polarization of a nucleus as a whole whereas in ^{144}Sm a particular structure of the lowest 2^- excitation plays a role of equal importance. If one excludes the coupling with the

[3]Radial form factors of dipole and spin-dipole interactions supposed to be the same

first one-phonon 2^- state in ^{144}Sm, the B(M2, $2^-_1 \to 0^+_{g.s.}$) value decreases twice.

The discussed B(M2)↓ probabilities were calculated with bare $g_{s,\ell}$ factors and most likely are the upper limits to their experimental values. Within the current approach $g_{s,\ell}$ are free parameters. We have already mentioned the investigations of B(M2) probabilities between low-lying states in odd-Z nuclei Eu, Pm, Pr [6]. It was shown that to describe these M2-transition rates taking into account magnetic core polarization, one needs to use $g_s^{eff} \le 0.6 g_s^{bare}$. We think it is reasonable to use the same values of the effective gyromagnetic factors in the present study though they are noticeably smaller than those derived from the magnetic moments of odd-mass nuclei [16]. The B(M2, $2^-_1 \to 0^+_{g.s.}$) values calculated with $g_s^{eff} = 0.6 g_s^{bare}$ are given in Table 1. They are of the same order of magnitude as B(M2, $11/2^-_1 \to 7/2^+_1$) in the neighbouring odd-Z nuclei.

It would be interesting to measure M2-transition rates for 2^-_1 states because one would get new information about nuclear magnetization and subtle features of low-lying excitations of unnatural parity. Evidently it is a difficult task since the corresponding values are very small. The $B(M2; 2^- \to 0^+_{g.s.})$ transitions were not detected in (n,n'γ) experiments on ^{142}Ce and ^{144}Sm [11, 12], where the 2^- levels were identified by their decay to 2^+_1 and/or 3^-_1 levels. A good tool to measure excitation probabilities of the states seems to be the backward inelastic electron scattering since spin-flip nuclear states are preferably excited in this reaction. The (e,e') scattering at large angles has already been used in studying high-lying M2-levels [17]. We think that the nuclei of N=84 isotones, where the 2^-_1 state is well separated from other 2^- states are better candidates for such an experiment. In nuclei with N=82 like ^{144}Sm, the two-phonon quadrupole - octupole 2^- state is too close to the lowest one-phonon state of the same spin and parity. So one cannot exclude a strong mixing of these two levels; moreover, the one-phonon state has much stronger excitation probability from the ground state.

4 Summary

The influence of the $M2$ core polarization on the γ- decay probability of the two-phonon quadrupole-octupole 2^- state was studied within the QPM. A strong increase in the B(M2,$2^-_1 \to 0^+_{g.s.}$) value due to the coupling of the two-phonon component with the M2-resonance at the excitation energy $E_x \simeq$ 7-11 MeV was found . The magnetic core polarization gives overwhelming contribution to B(M2) values. This effect is proposed to be measured in the backward inelastic scattering on even - even nuclei with N=84.

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