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Magnetic dipole states in ^{206}Pb

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Abstract. The fragmentation of the magnetic dipole strength in ^{206}Pb is studied in the framework of the quasiparticle–phonon nuclear model. The calculations reproduce the two-humped shape of the experimental distribution. As in ^{208}Pb there is an isoscalar 1^+ state at $E_x \simeq 5.7$ MeV in ^{206}Pb and its wavefunction contains sizable two-phonon components. It is shown that direct transitions from the ground state to two-phonon 1^+ states give a negligible contribution to the total excitation probability of the M1 resonance.

1. Introduction

In recent years important progress has been achieved in the experimental investigation of the magnetic dipole resonance. The history of the discovery and experimental studies of the M1 resonance has been dramatic (Brown and Raman 1980, Vdovin and Ponomarev 1982, Laszewski and Wambach 1985). Its existence in medium-mass and heavy nuclei was definitely proved only at the beginning of the present decade in experiments with protons of intermediate energy (Anantaraman *et al* 1981, Djalali *et al* 1982). But so far it is not clear what part of the theoretically predicted M1 strength has been observed. In particular, M1 transitions with a total strength of only $\sim 8\,\mu_0^2$ have been reliably identified in ^{208}Pb, to which the most attention has been paid by both theorists and experimentalists. An important contribution in clarifying the problem has been made by recent experiments with polarised photons (Weinhard *et al* 1982, Laszewski *et al* 1985, Ratzek *et al* 1986). First, very similar 1^+ levels with $E_x = 5.8$ MeV and $B(\mathrm{M1})\uparrow = 1.5\,\mu_0^2$ have been discovered in ^{208}Pb (Weinhard *et al* 1982) and ^{206}Pb (Ratzek *et al* 1986). These 1^+ states seem to be isoscalar magnetic dipole states. Second, 1^+ states with a total M1 strength of $19 \pm 2\,\mu_0^2$ have been detected by using the polarised tagged photon technique. If these data are confirmed, it will mean that an M1 resonance has been discovered in ^{206}Pb with an M1 strength in agreement with the traditional theoretical models.

Most theoretical investigations of the M1 resonance in heavy nuclei deal with the nucleus ^{208}Pb. The list of references is long and most of them can be found in reviews (Brown and Raman 1980, Vdovin and Ponomarev 1982, Laszewski and Wambach 1985), but no calculations have been performed for ^{206}Pb. Thus, Laszewski *et al* (1985) had to compare their data with the calculations for ^{208}Pb by Cha *et al* (1984). But the spectra of excitations of isotopes ^{208}Pb and ^{206}Pb differ appreciably. While ^{208}Pb is a doubly magic nucleus, the pairing correlations in the neutron system of ^{206}Pb play an important role. The energies of the lowest vibrational levels in ^{206}Pb are much less that those in ^{208}Pb. These

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two factors result in a much higher density of complex configurations in ^{206}Pb than in ^{208}Pb at the same excitation energy. Besides, the coupling of 1p–1h states to more complex ones increases when passing from a magic nucleus to its neighbour. These are the reasons for a stronger fragmentation of the M1 resonance in ^{206}Pb than in ^{208}Pb.

In this paper we consider the fragmentation of the M1 states in ^{206}Pb and calculate the contribution to the excitation probability of the M1 resonance of the direct transitions from the ground state to two-phonon 1^+ levels.

2. One-phonon magnetic dipole states in ^{206}Pb

An appropriate model for the problem in question is the quasiparticle–phonon nuclear model (QPM) (Soloviev 1976, 1978). In the QPM the coupling of one-phonon states to the two-phonon ones can be calculated microscopically in heavy nuclei with pairing correlations. The QPM formalism is described in detail in reviews by Vdovin and Soloviev (1983), Voronov and Soloviev (1983) and Vdovin *et al* (1985), and the fragmentation of the M1 resonance is considered within the QPM by Ponomarev *et al* (1979) and Vdovin *et al* (1979).

The effective particle–hole interaction in the QPM has a separable form. The radial form factor of the interaction is taken here as $R(r) = \mathrm{d}U/\mathrm{d}r$, where U is a central part of the Saxon–Woods potential. In the RPA, 1^+ states are generated by spin–spin and spin–isospin interactions. The contribution of the two-quasiparticle components with $\Delta l = 2$ is removed in the present calculations since their role in the energy range $E_x \leqslant 15$ MeV is negligible (Ponomarev and Vdovin 1980, Dao Tien Khoa *et al* 1986).

The parameters of the Saxon–Woods potential are taken from Chepurnov (1967), but for the energies of single-particle and single-hole subshells from the two neutron and proton major shells nearest to the Fermi surface we can use the values from Voronov and Dao Tien Khoa (1984). One can obtain a correct description of the low-lying levels of nuclei ^{207}Tl, ^{209}Bi and ^{207,209}Pb by taking into account the particle–vibration coupling within the QPM using these phenomenological single-particle and single-hole energies. The application of these single-particle spectra is also important for a correct description of the isoscalar 1^+ level of ^{208}Pb (Dao Tien Khoa *et al* 1986) and substructures in the photoabsorption cross section in ^{208}Pb (Voronov and Dao Tien Khoa 1984).

In the framework of the QPM the constant of the spin–isospin interaction $\kappa_1^{(01)}$ is determined by the position of the M1 resonance. We choose the value of $\kappa_1^{(01)}$ to get $E_x(\mathrm{M1}) = 7.85$ MeV in the RPA. The ratio $\kappa_1^{(01)}/\kappa_1^{(01)} = 0.1$ has been fixed to reproduce the properties of the isoscalar 1^+ state in ^{208}Pb (Dao Tien Khoa *et al* 1986). This estimation is in agreement with the results of Vergados (1971), Toki *et al* (1983) and Borzov *et al* (1984). The M1 strength distribution in ^{206}Pb calculated within the RPA is presented in figure 1(*a*). Due to the neutron pairing correlations we have three more 1^+ states in the energy region $E_x < 10$ MeV than in ^{208}Pb. They are neutron two-quasiparticle states with $E_x = 1.6$, 3.3 and 9.4 MeV, and they have a rather small value of $B(\mathrm{M1})\uparrow \simeq 0.1–0.3\ \mu_0^2$. The E_x and $B(\mathrm{M1})\uparrow$ values for the two 1^+ states with maximum values of $B(\mathrm{M1})$ are close in both the nuclei. The same is true for the structure of the states. In particular, the one-phonon state with $E_x = 6.08$ MeV has the same isoscalar structure as the state with $E_x = 5.85$ MeV in ^{208}Pb. Note that the $B(\mathrm{M1})$ probabilities are calculated with the effective gyromagnetic factors $g_s^{\mathrm{eff}} = 0.8\, g_s^{\mathrm{free}}$ and $g_l^{\mathrm{eff}} = g_l^{\mathrm{free}}$ and are close to the experimental ones (Laszewski *et al* 1985, Ratzek *et al* 1986).

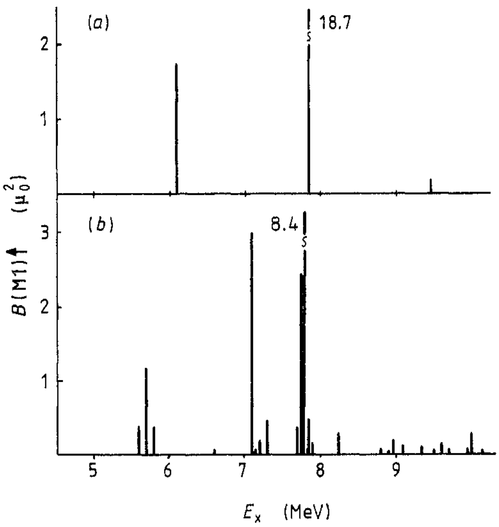

Figure 1. Distribution of the M1 strength in ^{206}Pb: (*a*) the RPA results; (*b*) the coupling of the one- and two-phonon states is taken into account.

3. Fragmentation of the magnetic dipole states

The RPA distribution of the M1 strength only roughly reproduces the experimental one. For a more adequate description of the experiment, it is necessary to take into account the interaction of the one-phonon states with the two-phonon states. For that we write the wavefunction of the excited 1^+ state as

$$\Psi_\nu(1^+M)=\left(\sum_i R_i(1^+\nu)Q^+_{1Mi}+\sum_{\substack{\lambda_1\lambda_2\\ i_1i_2}} P^{\lambda_2 i_2}_{\lambda_1 i_1}(1^+\nu)[Q^+_{\lambda_1\mu_1 i_1}Q^+_{\lambda_2\mu_2 i_2}]_{1^+M}\right)\Psi_0. \quad (1)$$

Here the following notation is used: $Q^+_{\lambda\mu i}$ is the phonon creation operator with angular momentum λ, its projection μ and RPA root number i; Ψ_0 is the wavefunction of the ground state of an even–even nucleus (phonon vacuum). The matrix element of the interaction between one- and two-phonon states $U^{\lambda_2 i_2}_{\lambda_1 i_1}(1^+i)$ is expressed in terms of the forward-going $(\psi^{\lambda i}_{j_1 j_2})$ and backward-going $(\varphi^{\lambda i}_{j_1 j_2})$ two-quasiparticle amplitudes of the one-phonon $Q^+_{1Mi}\Psi_0$, $Q^+_{\lambda_1\mu_1 i_1}\Psi_0$ and $Q^+_{\lambda_2\mu_2 i_2}\Psi_0$ wavefunctions. The expression for $U^{\lambda_2 i_2}_{\lambda_1 i_1}(1^+i)$ is given by Soloviev *et al* (1977, 1978), Voronov and Soloviev (1983) and Ponomarev *et al* (1979).

We are interested in the M1 strength distribution in ^{206}Pb in the energy range $4 \leqslant E_x \leqslant 10$ MeV, so three one-phonon 1^+ states from this energy range are included in the wavefunction (1). The two-phonon term of the wavefunction (1) consists of all two-phonon 1^+ states with $E_x < 12$ MeV and the coupling matrix elements $|U^{\lambda_2 i_2}_{\lambda_1 i_1}(1^+i)| \geqslant 0.01$ MeV. There are about 500 such two-phonon 1^+ states (we take into account phonons with angular momentum $\lambda_1, \lambda_2 = 1-7$).

The results are presented in figure 1(*b*). We obtain a rather strong fragmentation of the M1 strength in ^{206}Pb. It is much stronger than the one we get in the QPM for ^{208}Pb (Dao Tien Khoa *et al* 1986). The main reason for this is a much higher density of the two-phonon states in the range of the M1 resonance location in ^{206}Pb than in ^{208}Pb. In addition, the coupling matrix elements $U_{\lambda_1 i_1}^{\lambda_2 i_2}(1^+ i)$ are on average about 30% larger in ^{206}Pb. A characteristic feature of the calculated M1 strength distribution in ^{206}Pb is two maxima at $E_x = 7.1$ MeV and $E_x = 7.8$ MeV. There are also two maxima in the experimental distribution (see figure 2) at $E_x \simeq 7.2$ MeV and $E_x \simeq 7.9$ MeV but the ratio of their amplitudes is the inverse of the theoretical one.

In general we find the fragmentation of the M1 resonance in ^{206}Pb to be somewhat weaker than observed experimentally. In particular, among 1^+ levels in figure 1(*b*) there is one with $B(\mathrm{M1}) = 8\,\mu_0^2$ though the upper experimental value is $B(\mathrm{M1}) \simeq 2.5\,\mu_0^2$. Reasons for this may include the truncation of a complex configuration space by only a two-phonon subspace, the use of schematic effective forces, etc. Very often their influences are taken into account by including an additional artificial damping of the one-phonon states in the calculation. This can be introduced in different ways (Soloviev 1978, Bertsch *et al* 1983, Cha *et al* 1984). In the QPM the artificial damping of the one-phonon states can be attained by the strength function method (Soloviev 1978). To smear the M1 strength distribution, we introduce the following strength function:

$$b(\mathrm{M1}, E_x) = \frac{\Delta}{2\pi} \sum_{\nu} \frac{1}{(\eta_{1\nu} - E_x)^2 + \frac{1}{4}\Delta^2} B(\mathrm{M1}, 0^+_{\mathrm{GS}} \to 1^+_\nu). \qquad (2)$$

The sum in (2) is expanded over all 1^+ states (1) with energies $\eta_{1\nu}$. The strength function method is a powerful tool that allows us to calculate the M1 strength distribution without any information about $\eta_{1\nu}$ and $B(\mathrm{M1}, 0^+_{\mathrm{GS}} \to 1^+_\nu)$ (Soloviev 1978, Voronov and Soloviev 1983). The parameter Δ regulates the value of additional damping. If we use a Δ less than the average distance between 1^+ levels, the strength function (2) reproduces an exact picture of the $B(\mathrm{M1})$ distribution. We have calculated $b(\mathrm{M1}, E_x)$ with $\Delta = 0.3$ MeV by means of the program GIRES (Ponomarev *et al* 1981). At this value of Δ the maximum of $b(\mathrm{M1}, E_x)$ is about the same as that of the $B(\mathrm{M1})$ distribution in the experimental histogram. The strength function $b(\mathrm{M1}, E_x)$ (in units μ_0^2 per 100 keV, like the experimental data on $B(\mathrm{M1})$) is shown in figure 2. Instead of two bumps in the M1 strength distribution in ^{206}Pb there is only one bump in the M1 distribution in ^{208}Pb (Cha *et al* 1984, Dao Tien Khoa *et al* 1986).

The experimental probability of the M1 transitions for the energy range 6.7–8.1 MeV is equal to $19 \pm 2\,\mu_0^2$. Our calculations give the following numbers for this value: (*a*) $18.7\mu_0^2$ in the RPA; (*b*) $16.1\,\mu_0^2$ with coupling of one- and two-phonon states; (*c*) $13.2\,\mu_0^2$ with an additional damping.

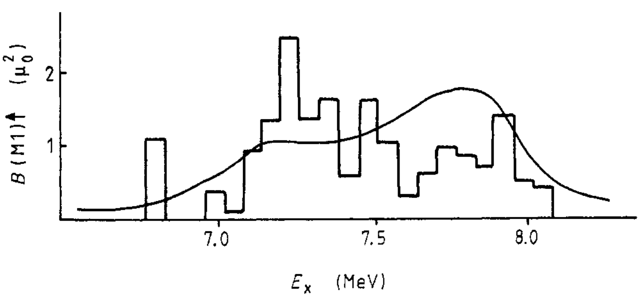

Figure 2. Distribution of the M1 strength in ^{206}Pb in the range of the M1 resonance. The experimental histogram is taken from Laszewski *et al* (1985). The strength function is calculated with $\Delta = 0.3$ MeV.

In concluding this section we would like to comment on some contradictions between the experimental results of Ratzek *et al* (1986) and Laszewski *et al* (1985) on the M1 strength above 7 MeV in ^{206}Pb. The experiments with tagged photons are sensitive to the total strength of the dipole γ transitions from the range ΔE_x whereas the nuclear resonance–fluorescence method (NRFM) is aimed at identifying individual levels. This is a weak point of the NRFM in ranges with a high level density, as in the case of the 1^+ state in ^{206}Pb. Only 24 dipole levels (among them only one 1^+ level) have been investigated by the NRFM in the range 4.3–7.5 MeV of ^{206}Pb (Ratzek *et al* 1986). It is clear that this number is much less than the real number of dipole states. Even in our calculations with a truncated two-phonon basis there are 58 1^+ states and almost the same number of 1^- states in the experimental energy interval. So, it seems to us that some of the 1^+ levels have been missed in the NRFM experiments.

4. The isoscalar 1^+ state

The RPA calculations (see figure 1(*a*)) point out that the isoscalar 1^+ state in ^{206}Pb is placed at $E_x \simeq 6.1$ MeV, i.e. at almost the same energy as in ^{208}Pb. The interaction with two-phonon states weakly influences the structure of 1^+_{is} state in ^{208}Pb (Lee and Pittel 1975, Dao Tien Khoa *et al* 1986), and thus the experimentally observed 1^+_{is} level in ^{208}Pb is practically a pure superposition of the two particle–hole components $(1h^{-1}_{11/2}, 1h_{9/2})_\pi$ and $(1i^{-1}_{13/2}, 1i_{11/2})_\nu$. The 1^+_{is} level is the lowest 1^+ state in ^{208}Pb, the next experimentally observed 1^+ state has $E_x = 7.3$ MeV (Martin 1986). This means that the density of 1^+ states in ^{208}Pb at $E_x \simeq 5$–7 MeV is very low and this is the reason for weak coupling of the 1^+_{is} state with complex configurations.

It follows from our calculations in ^{206}Pb that the interaction with two-phonon states influences visibly the one-phonon 1^+_{is} state, resulting in a noticeable fragmentation of its strength (figure 1(b)). The main part of its strength is distributed over three 1^+ levels—one of them has $E_x = 5.71$ MeV and $B(\mathrm{M1}) = 1.15\ \mu_0^2$, two others have $B(\mathrm{M1})\uparrow \simeq 0.3\ \mu_0^2$. The contribution of the one-phonon 1^+_{is} state to the norm of the wavefunction of the 1^+ state with energy 5.71 MeV is about 50%. If the QPM parameters are altered the $B(\mathrm{M1})$ values of the two weak 1^+ levels can change several times. But for any realistic set of the parameters we obtain at $E_x \simeq 5.6$–5.8 MeV a 1^+ level with $B(\mathrm{M1})\uparrow = 1.1$–$1.7\ \mu_0^2$ and the contribution of the one-phonon 1^+_{is} state to its structure is 45–60%. The other part of the norm of the state comes from two-phonon configurations. We believe this 1^+ state can be identified with the 1^+ level at $E_x = 5.80$ MeV with $B(\mathrm{M1})\uparrow = 1.5\ \mu_0^2$ observed in ^{206}Pb by Ratzek *et al* (1986).

The isoscalar 1^+ level in ^{208}Pb has also been investigated in (e, e′) and (d, ^{3}He) reactions (Hayakawa *et al* 1982, Mairle *et al* 1983, Müller *et al* 1985). What will be the influence of the two-phonon admixtures in the wavefunction of the 1^+ state in ^{206}Pb on the excitation probabilities? They cause the amplitude of the component $(1h^{-1}_{11/2}, 1h_{9/2})_\pi$ in the wavefunction of the 1^+ state to decrease to 0.6–0.7 whereas in the wavefunction of the 1^+_{is} state in ^{208}Pb its value is more than 0.87 (Hayakawa *et al* 1982). Thus, we can expect the cross section of the (d, ^{3}He) reaction with excitation of the 1^+ state in ^{206}Pb to be about 0.5–0.7 of that in ^{208}Pb. A similar effect will take place for (e, e′) scattering. The two-phonon admixtures cause the amplitude of the current transition density $\rho_{11}(r)$ of the 1^+_{is} state to decrease (figure 3). Note that shapes of the $\rho_{11}(r)$ of the 1^+_{is} states in ^{206}Pb and ^{208}Pb calculated in the RPA are very similar. The decrease of the surface peak of the $\rho_{11}(r)$ will suppress the electroexcitation of the 1^+ state in ^{206}Pb.

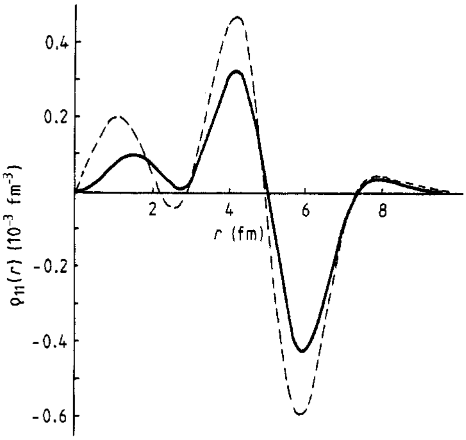

Figure 3. Current transition density $\rho_{11}(r)$ of the isoscalar 1^+ state in ^{206}Pb. The full curve is the calculation with the wavefunction (1), the broken curve is the RPA calculation.

5. Contribution of the two-phonon components to the excitation probability of the M1 resonance

To calculate the B(M1) values, we use the standard expression for the one-body operator of the M1 transition,

$$\mathcal{M}(\mathrm{M}1\mu)=\sum_{\substack{j_1m_1\\ j_2m_2}}\langle j_1m_1|\mathcal{M}(\mathrm{M}1\mu)|j_2m_2\rangle a^+_{j_1m_1}a_{j_2m_2} \tag{3}$$

where $\langle j_1m_1|\mathcal{M}(\mathrm{M}1\mu)|j_2m_2\rangle$ is a single-particle matrix element of this operator; $a^+_{j_1m_1}$ and $a_{j_2m_2}$ are nucleon creation and annihilation operators with the shell quantum numbers $j\equiv nlj$ and the momentum projection m. After Bogolubov's transformation from particle to quasiparticle operators $\alpha^+_{j_1m_1}$, $\alpha_{j_2m_2}$ and transformation of pair quasiparticle operators $\alpha^+_{j_1m_1}\alpha^+_{j_2m_2}$, $\alpha^+_{j_1m_1}\alpha_{j_2m_2}$, $\alpha_{j_2m_2}\alpha_{j_1m_1}$ to the phonon operators we can rewrite (3) in terms of phonons:

$$\begin{aligned}\mathcal{M}(\mathrm{M}1\mu)\equiv M_Q+M_{QQ}=\frac{\mu_0}{6}\Bigg(&\sum_i(Q^+_{1\mu i}-(-1)^\mu Q_{1-\mu i})\sum_{j_1j_2}\tfrac{1}{2}M^{(1)}_{j_1j_2}u^{(-)}_{j_1j_2}(\psi^{1i}_{j_1j_2}-\varphi^{1i}_{j_1j_2})\\ &+\sum_{\lambda_1i_1\lambda_2i_2}[(2\lambda_1+1)(2\lambda_2+1)]^{1/2}\sum_{j_1j_2j_3}M^{(1)}_{j_1j_2}v^{(+)}_{j_1j_2}\psi^{\lambda_1i_1}_{j_1j_2}\varphi^{\lambda_1i_1}_{j_1j_2}\\ &\times\begin{Bmatrix}1&\lambda_1&\lambda_2\\ j_3&j_1&j_2\end{Bmatrix}([Q^+_{\lambda_1\mu_1i_1}Q^+_{\lambda_2\mu_2i_2}]_{1\mu}+(-1)^\mu[Q_{\lambda_1\mu_1i_1}Q_{\lambda_2\mu_2i_2}]_{1-\mu})\Bigg).\end{aligned} \tag{4}$$

Here $u^{(-)}_{j_1j_2}$ and $v^{(+)}_{j_1j_2}$ are combinations of Bogolubov's coefficients; $M^{(1)}_{j_1j_2}$ is a reduced single-particle matrix element of $\mathcal{M}(\mathrm{M}1\mu)$. We have omitted terms $\sim Q^+Q$ in (4) for simplicity since they give no contribution to the transition matrix elements from the ground state to excited states (1).

If we consider the excitation of one-phonon states, then only the M_Q gives a

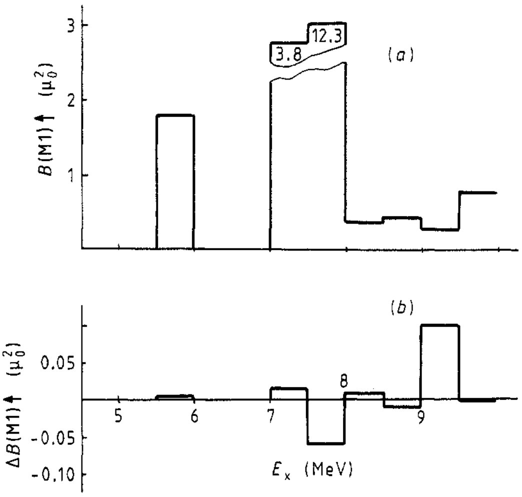

Figure 4. The histograms of the values (*a*) $B(\mathrm{M1}, 0^+_{\mathrm{GS}} \to Q^+ + Q^+Q^+)$ and (*b*) $\Delta B(\mathrm{M1}) = B(\mathrm{M1}, 0^+_{\mathrm{GS}} \to Q^+ + Q^+Q^+) - B(\mathrm{M1}, 0^+_{\mathrm{GS}} \to Q^+)$ in ^{206}Pb (see text for details).

contribution. The term M_{QQ} leads to two-phonon states $[Q^+_{\lambda_1\mu_1 i_1} Q^+_{\lambda_2\mu_2 i_2}]_{1\mu}$ being excited directly from the ground state. The excitation probability of two-phonon states is suppressed since $M_{QQ} \sim \psi\varphi$ while backward-going amplitudes φ are usually small. In the Tamm–Dancoff approximation $M_{QQ} = 0$ because $\varphi \equiv 0$; thus, a direct excitation of two-phonon states is forbidden in this approximation (Voronov *et al* 1984).

In our calculations with the wavefunction (1) both terms M_Q and M_{QQ} contribute. The interference of these terms depends not only on their amplitudes but also on the coefficients R and P in wavefunction (1). Despite the small excitation probability of an individual two-phonon state, their combined contribution to the total excitation probability of the states with given J^π from the energy interval ΔE_x at $E_x \sim 7$–8 MeV may be noticeable because of their high density.

Here we perform the calculations with the full operator (4). Let us consider now the contribution of the two-phonon component to the excitation probability of the M1 resonance in ^{206}Pb. We present the histogram of the $B(\mathrm{M1}, 0^+_{\mathrm{GS}} \to Q^+ + Q^+Q^+)$ calculated with the full operator (4) in figure 4(*a*) and the histogram of the difference $\Delta B(\mathrm{M1}) = B(\mathrm{M1}, 0^+_{\mathrm{GS}} \to Q^+ + Q^+Q^+) - B(\mathrm{M1}, 0^+_{\mathrm{GS}} \to Q^+)$ in figure 4(*b*). The value $B(\mathrm{M1}, 0^+_{\mathrm{GS}} \to Q^+)$ is calculated with the M_Q part of the operator $\mathcal{M}(\mathrm{M1}\mu)$ only, while the structure of 1^+ states is described by the wavefunction (1). We see that transitions to two-phonon components give a negligible contribution to the full M1 strength. The interference of the M_Q and M_{QQ} terms may be both destructive and constructive, but in all cases the changes are about 1%. The values $B(\mathrm{M1}, 0^+_{\mathrm{GS}} \to Q^+ + Q^+Q^+)$ and $B(\mathrm{M1}, 0^+_{\mathrm{GS}} \to Q^+)$ for the range 6.7–8.1 MeV, studied experimentally by Laszewski *et al* (1985), are equal to 16.1 μ_0^2 and 16.2 μ_0^2, respectively, while the total excitation probability of all the pure two-phonon states in this interval (without taking into account the coupling with one-phonon components) is equal to 0.04 μ_0^2.

Thus, the contribution of two-phonon states to the excitation probability of the M1 resonance is not important. But it may be important for some individual 1^+ level and must be taken into account in analysing low-lying states. This problem is discussed in detail by Ponomarev and Velchev (1986).

7. Conclusion

In this paper we have calculated the M1 strength fragmentation in ^{206}Pb caused by interaction with two-phonon states in the framework of the quasiparticle–phonon nuclear model. Though we find a fragmentation weaker than the experimental one, we reproduce the experimental data well by introducing a small additional damping to the theory. We qualitatively reproduce a two-peaked shape of the distribution.

We have satisfactorily described the properties of the newly observed 1^+ level in ^{206}Pb ($E_x = 5.8$ MeV, $B(\mathrm{M1})\uparrow = 1.5 \pm 0.5\ \mu_0^2$). We find that it has an energy of 5.6–5.8 MeV and an excitation probability 1.1–1.7 μ_0^2 (depending on the model parameters). The largest component of the state wavefunction is the particle–hole component $(1\mathrm{h}_{11/2}^{-1}, 1\mathrm{h}_{9/2})_\pi$ but unlike the 1^+ state in ^{208}Pb the two-phonon components are also noticeable. We would like to stress that the experimental M1 strength for both the M1 resonance and the isoscalar 1^+ level is reproduced in our calculations with an effective spin gyromagnetic factor $g_s^{\mathrm{eff}} = 0.8 g_s^{\mathrm{free}}$.

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