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Магнитный квадрупольный резонанс в сферических ядрах

Проведено теоретическое исследование распределения силы M2-переходов в спектрах сферических ядер. Показано, что взаимодействие одно- и двухфононных состояний оказывает сильное влияние на это распределение при энергиях $E_x > 15$ МэВ. Во всех ядрах обнаружена концентрация силы M2 -переходов в области энергии возбуждения 6-12 МэВ. Рассчитанная суммарная вероятность B(M2) в этом интервале энергий хорошо согласуется с экспериментальными данными в ^{90}Zr и ^{208}Pb. Расчеты указывают также, что группа состояний при энергии ~ 7 МэВ, обнаруженная в (e,e′) экспериментах на ^{58}Ni, является частью M2 -резонанса.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

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Magnetic Quadrupole Resonance in Spherical Nuclei

The fragmentation of the M2 -strength in spherical nuclei is studied within the quasiparticle-phonon nuclear model. It is shown that the interaction of the one- and two-phonon states affects strongly this distribution at the excitation energies $E_x > 15$ MeV. In all the nuclei the strength of the M2-transitions is concentrated in the excitation energy region of 6-12 MeV. At these energies the calculated total value of B(M2)↑ is in good agreement with the experimental data in ^{90}Zr and ^{208}Pb. The calculations show that a group of states observed in ^{58}Ni at an energy of about 7 MeV in the (e,e′) -experiments is a part of the M2-resonance.

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

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1. INTRODUCTION

In recent years a good deal of attention has been paid to the theoretical and experimental study of the giant resonances in medium and heavy atomic nuclei. The most important result of the experiments on the inelastic scattering of electrons at large angles is the discovery of the magnetic quadrupole resonance. The M2 -resonance was first detected in ^{208}Pb in the Naval Research Laboratory, Washington (NRL)[1]. These data were verified in the (e,e′) experiments with high resolution at the linear accelerator in Darmstadt, where the M2-resonance was also identified in ^{90}Zr[2-4]. The concentration of the M2 -strength in ^{90}Zr at an energy of $E_x \simeq 9$ *MeV* was observed earlier[5]. We should like to mention the investigations performed in the Ni isotopes by the group in NRL. They contain indirect indications to the existence of the 2^- states at the energies from 6 to 8.5 *MeV* in ^{58}Ni.

The M2 -resonance in ^{90}Zr and ^{208}Pb was studied in several papers. The Julich group[7,8] have studied the influence of the 2p-2h configurations on the distribution of M2 -strength within the finite Fermi-system theory. The calculations in the RPA were performed also within the MSI -model[2,3,9] and for ^{208}Pb with the effective separable spin-dipole forces[10]. It should be noted that in these calculations ^{90}Zr was considered as the doubly magic nucleus, i.e., the superconducting pairing forces in the proton system were not taken into account.

In this paper the M2 -resonance is studied in ^{58}Ni, ^{90}Zr, ^{120}Sn, ^{140}Ce and ^{208}Pb within the quasiparticle-phonon model[11,12]. The most detailed calculations have been performed for ^{90}Zr and ^{58}Ni. The comparison is made with the available experimental data and calculations of other authors.

2. FORMULAE AND NUMERICAL DETAILS

The Hamiltonian in the quasiparticle-phonon nuclear model includes the average field for protons and neutrons, the pairing interaction and the effective long-range forces[12]. The effective long-range forces generate in a doubly even nucleus the phonon excitations with different angular momenta and parities. The phonons with $I^{\pi} = 1^-, 2^+, \ldots, 7^-$ are generated by the separable multipole forces, whereas the phonons with $I^{\pi} = 1^+, 2^-, 3^+, \ldots, 6^-$ by the spin-multipole forces. Both the isoscalar and isovector parts of the effective forces have been taken into account. Thus the one-phonon states with $I^{\pi} = 2^-$ have been calculated in the RPA using the separable spin-dipole forces

$$\frac{1}{2}(\kappa_0^{(12)} + \kappa_1^{(12)} \vec{\tau}_1 \vec{\tau}_2) r_1 r_2 [\vec{\sigma}_1 Y_{1\mu}(\theta_1 \phi_1)]_{2^-} [\vec{\sigma}_2 Y_{1\mu}(\theta_2 \phi_2)]_{2^-} .$$

Besides the calculation in the RPA, we have performed the calculations taking into account the interaction of the one- and two-phonon states. The wave function of the 2^- state was taken in the form

$$\Psi_{\nu}(2^- M) = \{ \sum_i R_{\nu}(2^- i) Q^+_{2Mi} + \sum_{\substack{\lambda_2 \lambda_1 \\ i_2 i_1}} P^{\lambda_2 i_2}_{\lambda_1 i_1}(2^- \nu) [Q^+_{\lambda_1 \mu_1 i_1} Q^+_{\lambda_2 \mu_2 i_2}]_{2^- M} \} |0\rangle \qquad (1)$$

In (1) the following notation is used: $Q^+_{\lambda \mu i}$ is the phonon creation operator with angular momentum λ, projection μ and number i and $|0\rangle$ is the wave function of the ground state of a doubly even nucleus (phonon vacuum $Q_{\lambda \mu i}|0\rangle = 0$).). To find the energies and the structure of states described by the wave function (1), one should solve a very complicated system of nonlinear equations [12,13] of large dimension. As it is shown in ref.[12] it is simpler to calculate the M2-transition strength function $b(M2, \eta)$ which is determined as follows:

$$b(M2, \eta) = \sum_{\nu} B(M2, 0^+_{g.s.} \to 2^-_{\nu}) \frac{\Delta}{2\pi} \frac{1}{(\eta - \eta_{\nu})^2 + \Delta^2/4} . \qquad (2)$$

The reduced probability $B(M2; 0^+_{g.s.} \to 2^-_{\nu})$ of excitation of the 2^-_{ν} state from the ground one is calculated by the formula

$$B(M2, 0^+_{g.s.} \to 2^-_{\nu}) = | \sum_i R_{\nu}(2^- i) \langle 0 || \mathfrak{M}(M2) Q^+_{2\mu i} || 0 \rangle |^2 . \qquad (3)$$

Formula (3) for $B(M2, 0^+ \to 2^-_{\nu})$ is obtained under the assumption that the terms in the operator $\mathfrak{M}(M2)$, which do not change the number of quasiparticles (i.e., $\sim \alpha^+ \alpha$), give a negligible contribution to the probability of excitation of the 2^- states and therefore are not taken into account.

The average field is described by the Saxon-Woods potential the parameters of which have been chosen according to ref.[4]. The single-particle energies and the radial part of the wave functions have been found by solving numerically the Schrödinger equation by the method suggested in refs.[15]. As a result the single-particle spectra used in this paper differ from those obtained earlier[13] by the semianalytic method of solving the Schrödinger equation[16]. The new spectra have a larger density of the single-particle levels, and what is more essential, the quasibound state wave functions have the correct asymptotic behaviour. This made it possible to take into account the quasibound states with a relatively small width. The constants of the superconducting pairing interaction G_N and G_Z have been determined from the experimental values of the pairing energies. The parameters of the single-particle potential and the values of the constants $G_{N,Z}$ are given in *Table 1.*

The constants of the effective long-range forces have mainly been determined from the experimental data. We also used the estimates of papers[10,17]. The constants of the dipole forces have been chosen so as to describe correctly the E1-resonance energy and satisfy the condition that the energy of the first 1^- state be zero in the RPA. The latter condition allows one to exclude with good accuracy the influence of the spurious state which is caused by the breaking of the translational invariance[18]. The constants of the separable quadrupole and octupole interactions have been chosen so as to describe correctly the energies of the 2^+_1 and 3^-_1 states taking into account the two-phonon admixtures[13,19]. The ratio of the isoscalar and isovector constants has been determined by the formula

$$q^{(\lambda)} = \kappa_1^{(\lambda)} / \kappa_0^{(\lambda)} = -0.2 \times (2\lambda + 3). \qquad (4)$$

Formula (4) coincides with the estimates suggested by O.Bohr and B.Mottelson[17] up to a numerical factor (see also ref.[20]).

Table 1

The parameters of the Saxon-Woods potential and the pairing interaction constants

A		r_0 fm	V_0 MeV	$\varkappa$ fm^{-1}	α fm^{-1}	$G_{N,Z}$
59	N=31	1.31	46.2	0.413	1.613	0.280
	Z=27	1.24	53.7	0.308	1.587	0.302
91	N=53	1.29	44.7	0.413	1.613	0.168
	Z=39	1.24	56.9	0.338	1.587	0.194
121	N=71	1.28	43.2	0.413	1.613	0.122
	Z=51	1.24	59.9	0.346	1.587	0.136
141	N=83	1.27	46.0	0.413	1.613	0.116
	Z=59	1.24	57.7	0.349	1.587	0.122
209	N=127	1.26	44.83	0.376	1.587	0.074
	Z=83	1.24	60.3	0.371	1.587	0.080

The different numerical factor obtained for the oscillator single-particle potential [17] overestimates the energies of the isovector E2-resonance in the calculations with the Saxon-Woods potential. As is shown in papers [13,21] a correct position of the isovector E2-resonance is obtained in this case at $q^{(2)} \simeq (1.4 \div 1.5)$. The constants of the multipole forces with $\lambda > 3$ are taken less by a factor of 1.2-1.5 than those of ref. [17]. The collective states with low energy and $I > 3$ do not appear at these values of the constants. For the separable spin-multipole forces, the values of the constants are as follows:

$$\kappa_0^{(\lambda L)} = 0; \quad \kappa_1^{(\lambda L)} = -\frac{28 \times 4\pi}{A \langle r^{\lambda} \rangle^2} \frac{\text{MeV}}{\text{fm}^{2\lambda}}. \tag{5}$$

The dependence on A and λ in these formulae results from the qualitative considerations, and the numerical factor in the expression for $\kappa_1^{(\lambda L)}$ is chosen from the experimental energy of the M1-resonance in spherical nuclei [22]; it is close to the results of ref. [10]. Indeed, the constants (5) are not very accurate, but their change by a factor of 1.5-2 does not change the final results essentially. The dependence of the results on the constants $\kappa_0^{(12)}$ and $\kappa_1^{(12)}$ is discussed for the 2^- states in section 3. We have used the following values: $g_s^{eff} = 0.8 g_s^{free}$, $g_\ell^n = 0.0$, $g_\ell^p = 1.0$ for the effective gyromagnetic factors. The constants thus chosen (including g_s, g_ℓ-factors) have been used also for the calculation of the E1- and M1-resonances; a good agreement with experiment has been obtained [13,23]. The parameter Δ used for the calculation of the strength function $b(M2, \eta)$ is taken to be equal to 0.1 *MeV*.

3. *THE* M2 *-RESONANCE IN* ^{90}Zr

First we shall discuss the results for ^{90}Zr. The distribution of the M2-strength calculated in the RPA for different values of the constants $\kappa_0^{(12)}$, $\kappa_1^{(12)}$ is given in *Figs. 1a-d*. At the values of $\kappa_1^{(12)} \simeq -(30-40)\frac{4\pi}{A \langle r^2 \rangle^2}$ the main M2-strength is concentrated in two regions: $E_x =$ 8-12 *MeV* ($\Sigma B(M2)\uparrow \simeq 2900 \mu_N^2 \text{fm}^2$, where μ_N is the nuclear magneton) and $E_x \simeq$ 18-20 *MeV* comprising a state with the maximal value of $B(M2)\uparrow \simeq 1600-1800 \mu_N^2 \text{fm}^2$. This state is strongly collectivized. The change of the isoscalar constant $\kappa_0^{(12)}$ does not influence the distribution. Increasing of $|\kappa_0^{(12)}|$ results in the concentration of the M2-strength in individual states only, i.e., in the decrease in the number of the 2^--levels with a considerable value of $B(M2)\uparrow$. The spin-dipole effective n-p-forces are so weak at $\kappa_0^{(12)} = 0.9 \kappa_1^{(12)}$ that the one-phonon states consist either of neutron or proton two-quasiparticle components only. With decreasing $|\kappa_1^{(12)}|$ the aforesaid regions of strong M2-transitions approach each other and the M2-strength concentrates at $E_x \simeq 10$ *MeV*. The strongest 2^--state becomes less collective and its energy and value of $B(M2)$ decrease. It should be noted that all the 2^--states with large values of $B(M2)$ correspond to the transitions over one shell.

Table 2 shows the experimental and theoretical data of various authors on the total M2-transition probability in ^{90}Zr in

the interval $\Delta E_x = 8\text{-}10$ *MeV* $B_{\Sigma}(M2) = \sum_{i \in \Delta E_x} B(M2, 0^+_{g.s.} \to 2^-_i)$.
These data show that with the constants (5) the theoretical results in the RPA are in good agreement with experiment. The

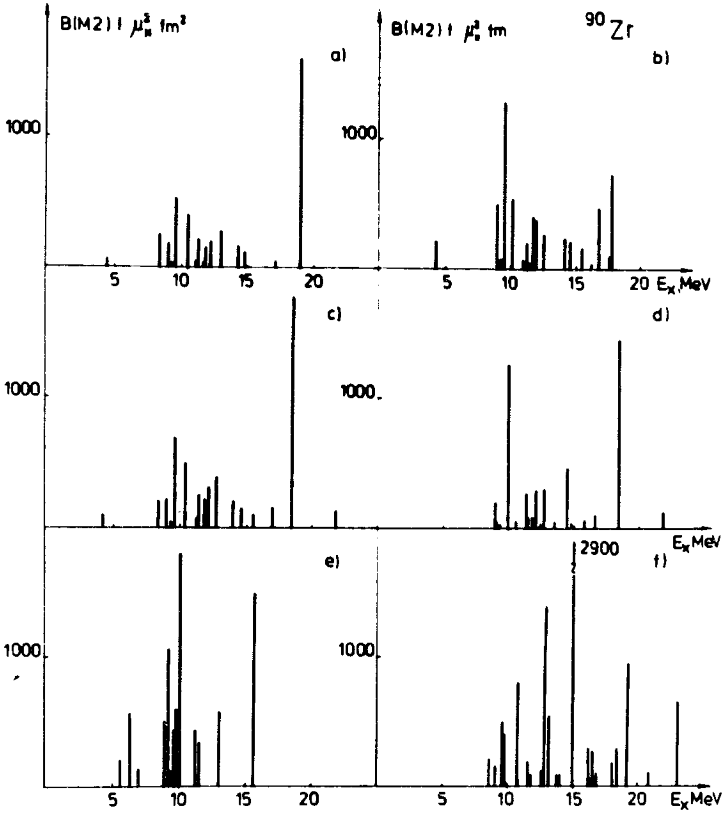

Fig. 1. Magnetic quadrupole resonance in ^{90}Zr. *Calculations in the RPA:*
a) $\kappa_0^{(12)} = 0$ $\kappa_1^{(12)} = -37 \times 4\pi/A\langle r\rangle^2$ MeV·fm^{-2}
b) $\kappa_0^{(12)} = 0$ $\kappa_1^{(12)} = -14 \times 4\pi/A\langle r\rangle^2$ MeV·fm^{-2}
c) $\kappa_0^{(12)} = 0$ $\kappa_1^{(12)} = -28 \times 4\pi/A\langle r\rangle^2$ MeV·fm^{-2}
d) $\kappa_0^{(12)} = 0.9\kappa_1^{(12)}$ $\kappa_1^{(12)} = -28 \times 4\pi/A\langle r\rangle^2$ MeV·fm^{-2}
e) Calculations within the MSI-model /3/. *The gyromagnetic factors are free.*
f) Calculation within the theory of finite Fermi-systems /8/. *The gyromagnetic factors are free.*

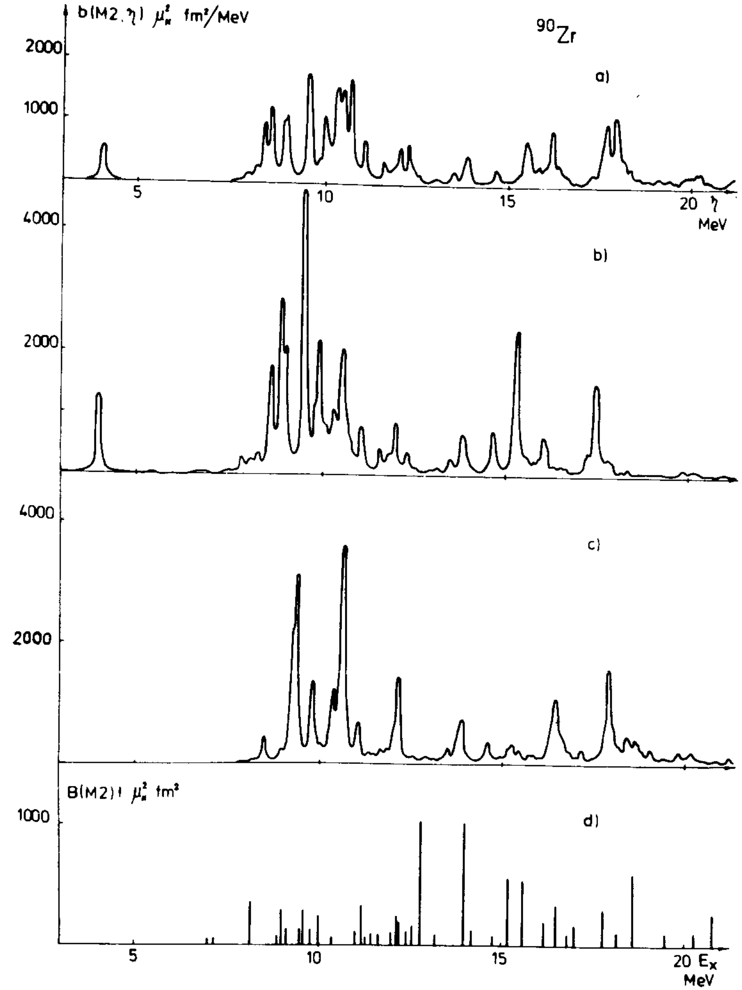

Fig. 2. The M2*-resonance in* ^{90}Zr *taking into account the one- and two-phonon states:*
a) $\kappa_0^{(12)} = 0$ $\kappa_1^{(12)} = -28 \times 4\pi/A\langle r\rangle^2$ MeV·fm^{-2}
b) $\kappa_0^{(12)} = 0$ $\kappa_1^{(12)} = -14 \times 4\pi/A\langle r\rangle^2$ MeV·fm^{-2}
c) $\kappa_0^{(12)} = 0.9\kappa_1^{(12)}$ $\kappa_1^{(12)} = -28 \times 4\pi/A\langle r\rangle^2$ MeV·fm^{-2}
d) Calculation within the theory of finite Fermi-systems taking into account the mixing of 1p−1h *and* 2p−2h *configurations* /8/.

change of the constants $\kappa_0^{(12)}$ and $\kappa_1^{(12)}$ within reasonable limits results in the change of $B_\Sigma(M2)$ by a factor of 1.5-2.0. Our results for $B_\Sigma(M2)$ are close to the results of calculations within the theory of finite Fermi-systems with free values of the gyromagnetic factors [8]. But the general picture of distribution of the M2-strength in the excitation energy region 0-25 *MeV* is more close to the calculations by the MSI-model [3] (*fig. 1e*). The comparison of *Figures 1b)* and *1e)* shows that the results obtained in ref. [3] are very close to ours at $\kappa_1^{(12)} \simeq -10 \times 4\pi / A \langle r^2 \rangle$ MeV·fm^{-2}. Here we can separate two regions which concentrate strong M2-transitions, the maximum of B(M2) being at an energy of $E_x \simeq 10$ *MeV*. The distribution of the M2-strength calculated within the theory of finite Fermi-systems in the RPA is of a quite different form (*fig. 1f*). The strong M2-transitions appear in a wide energy region from 8 to 20 *MeV*, and the maximum of B(M2) is at an energy of $E_x = 15$ *MeV*. As is shown in ref. [8] the main features of the distribution are slightly sensitive to the parameters of residual forces (see *Fig. 36* of ref. [8]). The difference between the predictions of this paper and ref. [8] is caused mainly by different single-particle schemes. The single-particle neutron and proton schemes for ^{90}Zr given in ref. [8] differ from our schemes by a much lesser density of hole levels and smaller distance between the unfilled and neighbouring major shells. We have performed the calculations of the M2-resonance in ^{90}Zr using the single-particle schemes of ref. [8] and our effective forces. The result is rather close to that in *Fig. 1f)*. This means that the concrete form of the effective forces is of no importance.

The interaction of the one- and two-phonon states changes strongly the distribution of the M2-strength, especially at high excitation energies. The strength function $b(M2, \eta)$ calculated at different values of the constants $\kappa_0^{(12)}$ and $\kappa_1^{(12)}$ is shown in *Fig. 2a)-c)*. In these calculations the one-phonon part of the wave function (1) included 14 one-phonon 2^- states with the largest values of B(M2) in the excitation energy interval 0-25 *MeV*. These 14 states exhaust 90% of the total M2-strength in this interval. The two-phonon part of the wave function included more than 800 states for which the matrix element of interaction with the one-phonon states was not less than 3% of its

Table 2

Experimental and theoretical values of $\sum_{i \in \Delta E_x} B(M2, 0^+ \to 2_i^-) \mu_N^2 \, fm^2$

for $\Delta E_x = 8\text{-}10$ ***MeV*** **in** ^{90}Zr **and** $\Delta E_x = 6.1\text{-}8.4$ ***MeV*** **in** ^{208}Pb

Nuclei	Exp. Refs. [2,3]	Present results: $\mathcal{X}_0^{(12)} = 0$, $\mathcal{X}_1^{(12)} = -\frac{28 \times 4\pi}{A\langle r\rangle^2} \frac{MeV}{fm^2}$		$\mathcal{X}_0^{(12)} = 0$, $\mathcal{X}_1^{(12)} = -\frac{14 \times 4\pi}{A\langle r\rangle^2} \frac{MeV}{fm^2}$		$\mathcal{X}_0^{(12)} = 0.9\,\mathcal{X}_1^{(12)}$, $\mathcal{X}_1^{(12)} = -\frac{28 \times 4\pi}{A\langle r\rangle^2} \frac{MeV}{fm^2}$		MSI-model Refs. [2,3]	Ref. [10]	Theory of finite Fermy-systems. Effective (free) M2-operator Ref. [8]	
		RPA	$Q^+ + Q^+Q^+$	RPA	$Q^+ + Q^+Q^+$	RPA	$Q^+ + Q^+Q^+$	1p-1h	1p-1h	1p-1h	1p-1h, 2p-2h
^{90}Zr	1100±100	1090	1100	1900	2100	1420	1000	4500	-	640(1280)	(1190)
^{208}Pb	8500±750	9700	-	12600	-	9850	-	13000	11000	11600	9100

maximal value. The lower group of strong M2-transitions is slightly affected by the two-phonon admixtures. It almost conserves its position, the width of location and the total strength of the M2-transitions. The $B_{\Sigma}(M2)$-value changes slightly too. From *Table 2* one can see that the $B_{\Sigma}(M2)$ -values calculated both in the RPA and taking into account the interaction of the one- and two-phonon states are in satisfactory agreement with experimental data. Strong changes occur in the collective state at $E_x = 18$ *MeV*. Its interaction with the two-phonon states causes almost a complete spreading of the high-lying branch of the M2-resonance. *Table 3* gives the M2-strength distribution in the spectrum of ^{90}Zr obtained both in the RPA and taking into account the interaction of one- and two-phonon states (the constants $\kappa_0^{(12)}$ and $\kappa_1^{(12)}$ correspond to eq. (5)). It is seen that the M2-strength corresponding to the strong 2^--state at $E_x = 18$ *MeV* is spread in the interval of about 10 *MeV*. *Figure 3* shows the strength function describing the fragmentation of this state only (without allowing for the influence of other one-phonon 2^--states). *Figure 3* clearly demonstrates the ap-

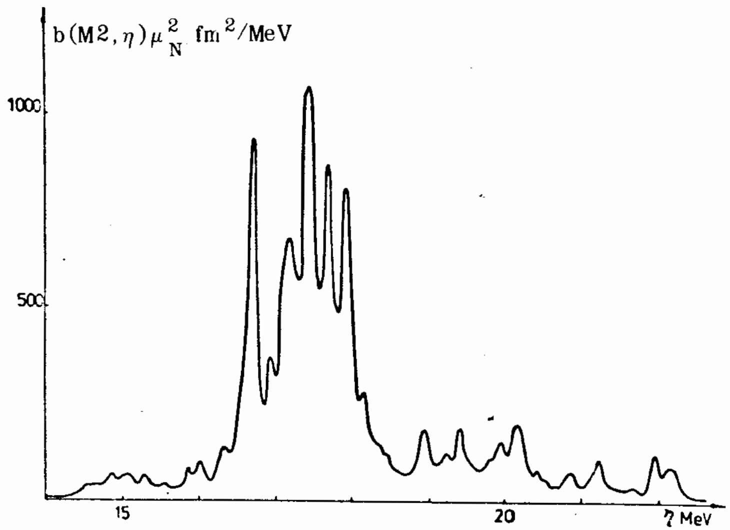

Fig. 3. The strength distribution of the one-phonon state with $E_x = 18$ *MeV (For the constants see Fig. 1c).*

Table 3

M2-strength distribution in ^{90}Zr and ^{58}Ni calculated in RPA and taking into account the interaction of one- and two-phonon states

Nuclei	ΔE Mev	0-6	6-8	8-10	10-12	12-14	14-16	16-18	18-20	20-25
^{90}Zr	$\sum_{\Delta E} B(M2\uparrow)\ \mu_N^2 fm^2$ RPA	90	-	1090	930	640	430	130	1800	-
	$\int_{\Delta E} b(M2,\eta)d\eta\ \mu_N^2 fm^2$	100	54	1100	1300	400	440	790	410	300
^{58}Ni	$\sum_{\Delta E} B(M2)\uparrow\ \mu_N^2 fm^2$ RPA	-	-	440	930	220	220	240	-	1200
	$\int_{\Delta E} b(M2,\eta)d\eta\ \mu_N^2 fm^2$	-	590	530	300	250	370	300	110	450

pearance of the width of an "infinitely narrow" resonance due to the interaction with more complex configurations. The reason of the strong fragmentation of the high-lying branch of the M2 - resonance is a high collectivity of this state, resulting in a strong coupling with the two-phonon states, and a large density of the two-phonon states at the excitation energy $E_x = 18$ *MeV*. To what extent this result is stable to the change of the constants of the effective spin-dipole forces, one can see from *Figs. 2a), 2b)* and *2c)*. The absence of the strong concentration of the M2 -strength at large excitation energies is a common feature of these pictures. At the values $\kappa_1^{(12)} \simeq -10 \times 4\pi/A \langle r\rangle^2 \frac{\text{MeV}}{\text{fm}^2}$ the collective state with $E_x = 18$ *MeV* is absent already in the RPA; at larger values of $|\kappa_1^{(12)}|$ it spreads over the two-phonon states. The distributions of the M2 -strength shown in *Fig. 2a)-c)* are much closer to each other than those calculated in the RPA. So, the essential concentration of the M2 -strength is in the interval $E_x = 8$-12 *MeV* which comprises 45% of the total value of B(M2) in the interval 0-25 *MeV*.

The influence of the interaction with complex configurations on the M2 -resonance in ^{90}Zr has been studied also in the theory of finite Fermi-systems /8/. The results of the corresponding calculations are given in *Fig. 2d)* (see also *Fig. 36*, ref. /8/). As it is seen from *Figs. 1f)* and *2d)* the interaction of 1p-1h and 2p-2h configurations results in a noticeable fragmentation of the M2 -strength, but the main features of the distribution is not changed. *Table 2* shows also that the value of B_Σ(M2) in these calculations is slightly changed as well as in our calculations.

It has already been mentioned that the set of parameters used in our paper allows one to describe satisfactorily the available experimental data on the M1-resonance in spherical nuclei /23/. *Figure 4* shows the M1 -resonance in ^{90}Zr calculated both in the RPA (*Fig. 4a*). and taking into account the interaction of the one- and two-phonon states (*Fig. 4b*). The two-phonon admixtures do not influence strongly the M1 -resonance, and therefore the main strength of the M1 -transitions is concentrated in a narrow region around $E_x = 8$ *MeV*. The M1 - and M2 -resonances in ^{90}Zr are overlapped, and the total photoabsorption cross section for the M1 -resonance is larger by an order of two than for the M2 -resonance.

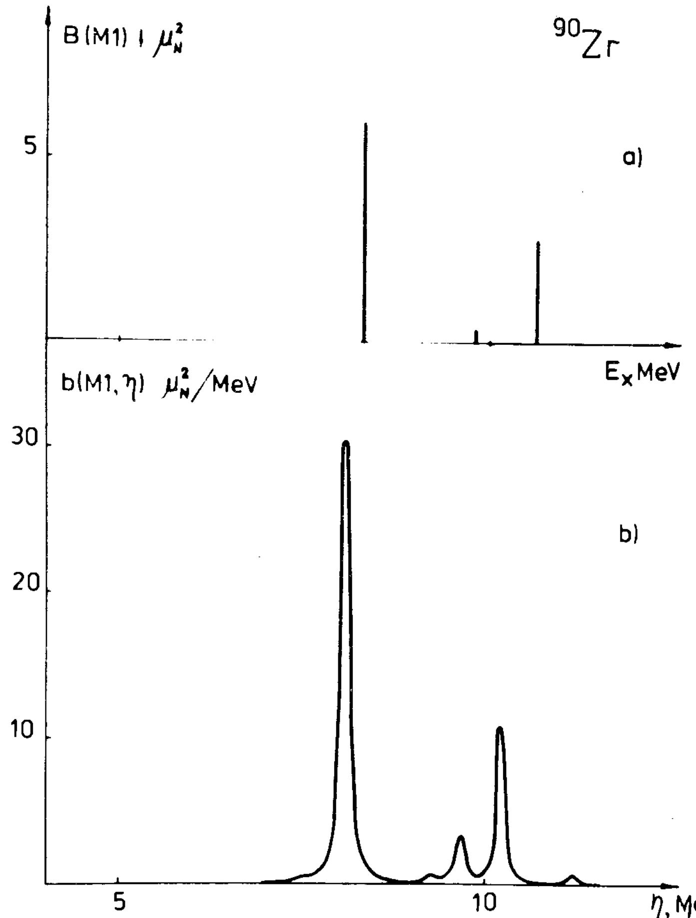

Fig. 4. The M1*-resonance in* ^{90}Zr *a) Calculation in the RPA. b) The strength function* b(M1, η) *taking into account the interaction of the one- and two-phonon states. The constants*: $\kappa_0 = 0$, $\kappa_1 = -28 \times 4\pi/A$ MeV.

4. *THE* M2 *-RESONANCE IN* ^{58}Ni

The distribution of the M2 -strength in ^{58}Ni calculated in the RPA has the same specific features as in ^{90}Zr (*Fig. 5a*). In ^{58}Ni the regions of the strong M2 -transitions lie at somewhat larger excitation energies: $E_x = 9.5$-12.5 *MeV* ($\Sigma B(M2)\uparrow = 1570 \mu_N^2$ fm^2) and $E_x = 20$ *MeV* ($\Sigma B(M2)\uparrow \simeq 1200 \mu_N^2$ fm^2). The interaction of the one- and two-phonon states changes this distribution considerably (*fig. 5b*). First, as in ^{90}Zr the high-lying collective state strongly spreads. It is fragmented even stronger since at the excitation energy of 18-22 *MeV* in ^{58}Ni there is a group of the two-phonon states this state is coupled with very strongly. Second, the group of the M2-transitions lying at an energy of 9.5-12.5 in the RPA lowers greatly and its mean energy is around 7 *MeV*. The data on the distribution of the M2-strength obtained both in the RPA and taking into account the interaction of the one- and two-phonon states are given in *Table 3*. A considerable concentration of M2-strength at an energy of $E_x \simeq 7$ *MeV* forces us to apply to the results of the (e,e′)-experiments /6/. As it was already mentioned in the Introduction, a group of states was observed at an energy of 6-8 *MeV* in ^{58}Ni, which could not be established to consist either of the 1^+ or 2^--states. The theoretically calculated M1-transitions at this energy /23/ are not in agreement with the experimen-

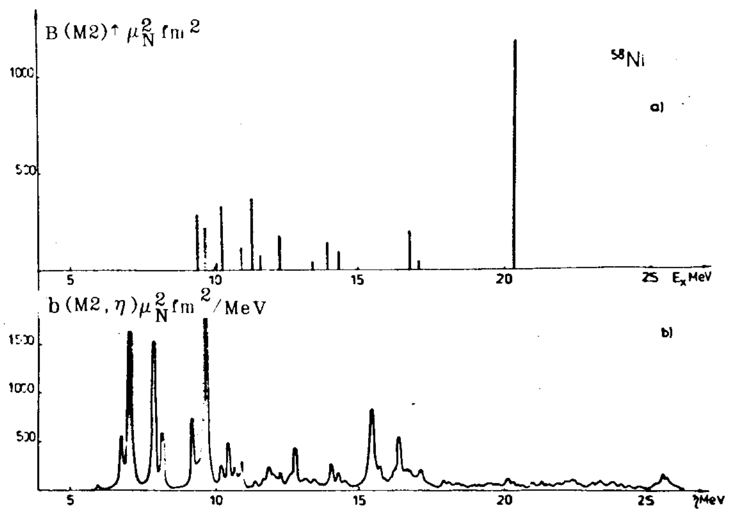

Fig. 5. The M2*-resonance in* ^{58}Ni *a) Calculation in the RPA. b) The strength function* $b(M2,\eta)$ *taking into account the interaction of the one- and two-phonon states. The constants:* $\kappa_0^{(12)} = 0$; $\kappa_1^{(12)} = -28 \times 4\pi / A \langle r \rangle^2$ MeV · fm^{-2}.

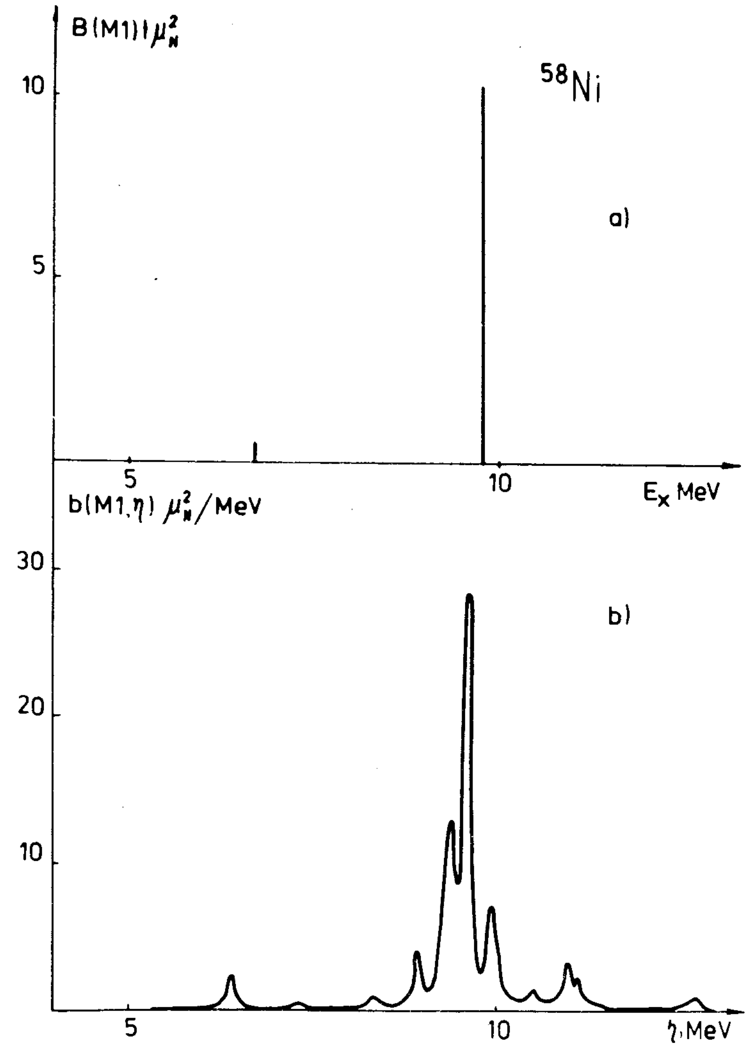

Fig. 6. The M1*-resonance in* ^{58}Ni: *a) Calculation in the RPA. b) The strength function* $b(M1,\eta)$ *taking into account the interaction of the one- and two-phonon states. The constants:* $\kappa_0 = 0$; $\kappa_1 = -28 \times 4\pi / A$ MeV.

tal value of $B(M1)\uparrow$ (see *Fig. 6*), though for the group of 1^+ states at 10-11 *MeV* the results of calculation are in good agreement with the experimental data. According to the estimates of ref. /6/

if the states at 6-8 *MeV* have $I^{\pi} = 2^{-}$ then $\Sigma B(M2)\uparrow \simeq 500\,\mu_N^2 fm^2$. The total value of $B(M2)\uparrow$ in this interval in our calculation is $700\,\mu_N^2 fm^2$; this is in agreement with experiment. Thus, our results testify to the assumption that a group of states observed in ^{58}Ni at 6-8 *MeV* /6/ consists mainly of 2^- states. It should be emphasized that this result is a consequence of the interaction of one- and two-phonon states.

5. *THE M2-RESONANCE IN THE NUCLEI WITH A >100*

In this section we shall briefly discuss the predictions of the quasiparticle-phonon nuclear model for the M2-resonance in heavier nuclei. The distribution of the M2-strength in the interval $E_x = 0 \div 20$ *MeV* in ^{120}Sn, ^{140}Ce and ^{208}Pb is given in *Fig. 7*. The calculation has been performed in the RPA with the values of the constants (5). Though the main features of these distributions are almost the same as in ^{90}Zr and ^{58}Ni, certain differences should be mentioned. The nuclei with A >100 have one region of strong M2-transitions with width of about 10 *MeV* bounded by the states with the largest value of B(M2) instead of two regions in ^{90}Zr and ^{58}Ni. The mean energy of the region is lowered with increasing A. The results of calculation for ^{90}Zr and ^{58}Ni give evidence for the strong fragmentation of states at the energies $E_x > 15$ *MeV*.

Indeed, the calculation of the strength function $b(M2,\eta)$ in ^{120}Sn shows that in this nucleus the M2-strength at the energies $E_x > 15$ *MeV* is distributed in a wide interval ΔE_x, its considerable concentration is observed only at $E_x \simeq 7$-10 *MeV (fig. 8)*. Note that due to the computational difficulties $b(M2,\eta)$ in ^{120}Sn has been calculated with a very limited set of the two-phonon states. Nevertheless, we think that this limitation only weakens the fragmentation of the one-phonon states.

Thus, our calculations show that a noticeable concentration of the M2-strength is observed in all spherical nuclei with $60 < A < 210$ at the energies $E_x = 6$-12 *MeV*. The quasiparticle-phonon model describes satisfactorily the total strength of the M2-transitions in this energy region. This is confirmed once

more by the comparison of the experimental data and our results for ^{208}Pb (see *Table 2* which shows the data obtained by other authors too). Another important feature of our calculation is the absence of the regions with strong concentration of the M2-strength at $E_x > 12$ *MeV*.

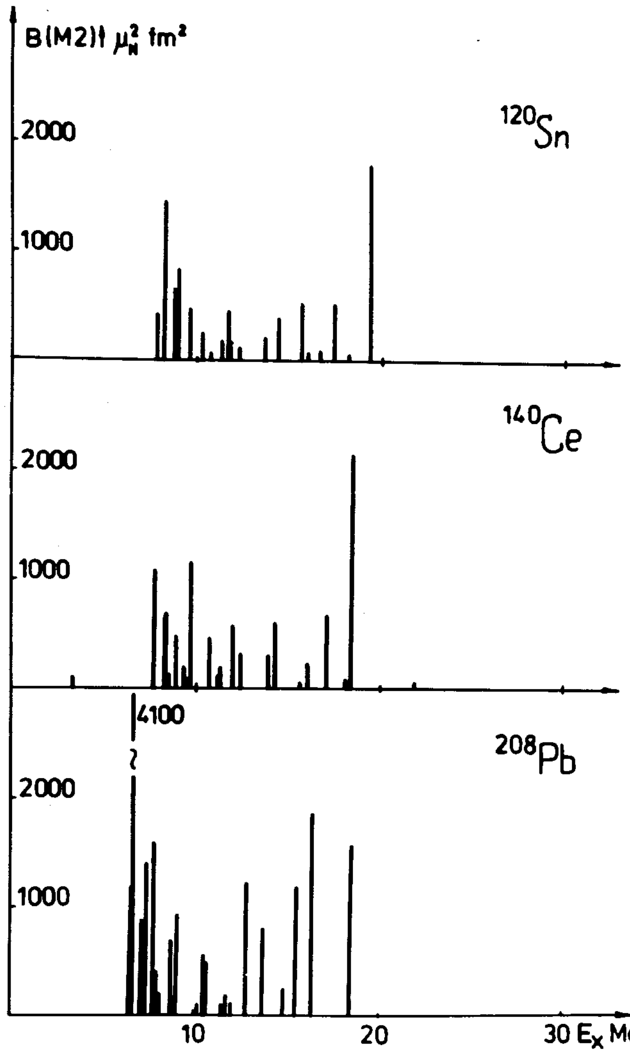

Fig. 7. The M2-resonance in ^{120}Sn, ^{140}Ce *and* ^{208}Pb. *Calculation in the RPA. The constants:* $\kappa_0^{(12)} = 0$, $\kappa_1^{(12)} = -28 \times 4\pi / A \langle r \rangle^2$ MeV·fm^{-2}.

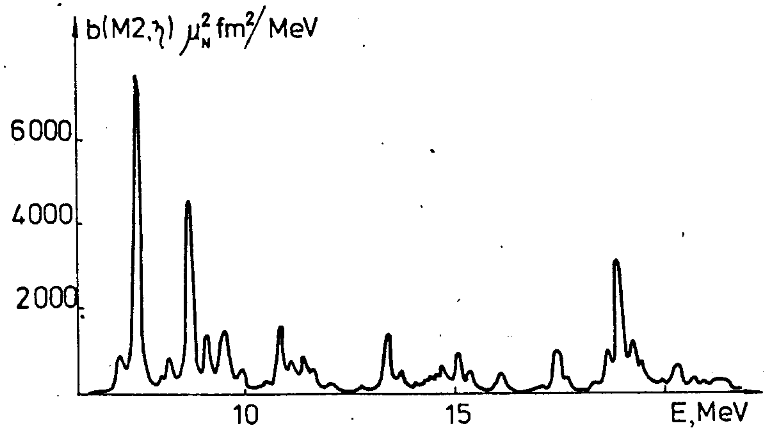

Fig. 8. The strength function $b(M2,\eta)$ *in* ^{120}Sn *calculated taking into account the interaction of the one- and two-phonon states. The constants:* $\kappa_0^{(12)} = 0$; $\kappa_1^{(12)} = -28 \times 4\pi / A \langle r \rangle^2$ MeV·fm^{-2}.

6. CONCLUSION

Based on the results of this paper we can make two conclusions. First, this paper together with the papers /13,23/ shows that within the quasiparticle-phonon model with the unique set of parameters one can describe satisfactorily a large portion of the experimental data on the $E\lambda$, M1- and M2-resonances and radiative widths of the neutron resonances in spherical doubly even nuclei. We would like to note that at the same time the quasiparticle-phonon model describes well the low-lying nuclear excitations. On the other hand our calculations show that an essential part of the total M2-strength is concentrated in all spherical nuclei at the excitation energies from 6 to 10 *MeV*. At higher excitation energies the regions with such a strong concentration of the M2-strength are absent. Note, that the regions of existence of the M1- and M2-resonances are overlapped, making thus it difficult to identify them.

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