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DESCRIPTION OF GIANT MULTIPOLE RESONANCES IN SPHERICAL NUCLEI

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At present an enormous experimental material on the properties of giant multipole resonances (GMR) is accumulated and continuously widened with the new data. For a most complete classification of the GMR properties see the reviews [1,2]. In recent years much progress has been achieved in describing the GMR widths. It has been favoured by the understanding of the key role in describing the GMR properties of the coupling of simple one-phonon states with complex configurations. An important role of the quasiparticle-phonon interaction for the fragmentation of one-phonon states and thus for the formation of the GMR widths has been pointed out as far back as 1968-1971 [3,4]. Now this view-point is generally accepted. The basic theoretical works on the description of the GMR are reviewed in paper [5]. Note, that it is in paper [6] that the first quantitative results on the properties of electric GMR taking into account the quasiparticle-phonon interaction have been obtained. Equations, allowing for the quasiparticle-phonon interaction, for the fragmentation of one-quasiparticle and one-phonon states have been derived in papers [7,8]. To calculate the GMR widths, one should take into account both the spreading widths $\Gamma^{\downarrow}$ and the escape widths $\Gamma^{\uparrow}$. However, the latter have a smaller value as compared to the first ones in medium and heavy nuclei, therefore, the main problem is to calculate $\Gamma^{\downarrow}$ by taking into account the 2p-2h configurations. Within the quasiparticle-phonon nuclear model (QPM) [9] this problem is solved by introducing the two-phonon components into the wave function. General equations of this type are given in papers [9,10]. The GMR properties of many spherical nuclei (magic and nonmagic) with $58 \leq A \leq 208$ have been studied in detail within the QPM in papers [11-14]. In describing the electric GMR in spherical nuclei, the 2p-2h configurations have been taken into account in [15-21]. As a rule, the calculations are performed for twice magic nuclei.

The present paper is a sequel of the study of the electric GMR: the characteristics of the isoscalar quadrupole resonances are calculated, the QPM is compared with the nuclear field theory (NFT) [18,19] and the influence of corrections due to the Pauli principle in the two-phonon components of the GMR wave functions on the GMR excitation probabilities is studied.

1. BASIC FORMULAE AND DETAILS OF CALCULATION

Within the QPM the fragmentation is calculated by using as a basis the one-phonon states, the wave functions of which are calculated in the RPA. While constructing the basis, all the model parameters are fixed. The strength function method is used, and the reduced transition probabilities, transition densities, scattering cross sections and other nuclear characteristics are calculated immediately without solving the corresponding secular equations [9].

The QPM Hamiltonian contains the terms describing the average nuclear field as the Saxon-Woods potential, pairing interactions, multipole-multipole and spin-multipole - spin-multipole isoscalar and isovector including charge-exchange interactions. The general properties of the Hamiltonian are presented in paper [9]. In the given paper we shall dwell upon the particle-hole channel alone.

The excited state wave function of a doubly even spherical nucleus can be written down as

$$\Psi_\nu(JM) = \{ \sum_i R_i(J\nu) Q^+_{JMi} + \sum_{\substack{\lambda_1 i_1\\ \lambda_2 i_2}} P^{\lambda_1 i_1}_{\lambda_2 i_2}(J\nu)[Q^+_{\lambda_1\mu_1 i_1} Q^+_{\lambda_2\mu_2 i_2}]_{JM}\}\Psi_0 , \quad (1)$$

where Ψ_0 is the phonon vacuum and the ground state wave function. By calculating an average value of the QPM Hamiltonian over the states (1) and using the variational principle, one can get a system of equations for determining the coefficients R and P. In paper [10] the secular equation in the two-phonon space is obtained, and it is shown that a large set of diagrams is summed. In this case many diagrams are used which influence slightly the fragmentation of one-phonon states. By rejecting them, one can pass to approximate equations. In this case the secular equation is written down in the one-phonon space as

$$\mathcal{F}(\eta_\nu) = \det||(\omega - \eta_\nu)\delta_{ii'} - \frac{1}{2}\sum_{\substack{\lambda_1 i_1\\ \lambda_2 i_2}} \frac{U^{\lambda_1 i_1}_{\lambda_2 i_2}(Ji)\, U^{\lambda_1 i_1}_{\lambda_2 i_2}(Ji')\{1 + \frac{1}{2}K^J(\lambda_1 i_1, \lambda_2 i_2)\}}{\omega_{\lambda_1 i_1} + \omega_{\lambda_2 i_2} + \Delta\omega(\lambda_1 i_1, \lambda_2 i_2) - \eta_\nu}|| = 0 , \quad (2)$$

where

$$K^J(\lambda_1 i_1, \lambda_2 i_2) = \sum_{j_1 j_2 j_3 j_4} (-)^{j_2+j_4-J}(2\lambda_1+1)(2\lambda_2+1)\begin{Bmatrix} j_1 & j_2 & \lambda_2\\ j_4 & j_1 & \lambda_1\\ \lambda_1 & \lambda_2 & J\end{Bmatrix} \times \quad (3)$$

$$\times [\psi^{\lambda_1 i_1}_{j_3 j_4}\psi^{\lambda_1 i_1}_{j_1 j_4}\psi^{\lambda_2 i_2}_{j_3 j_2}\psi^{\lambda_2 i_2}_{j_1 j_2} - \phi^{\lambda_1 i_1}_{j_3 j_4}\phi^{\lambda_1 i_1}_{j_1 j_4}\phi^{\lambda_2 i_2}_{j_3 j_2}\phi^{\lambda_2 i_2}_{j_1 j_2}],$$

$\psi^{\lambda_1 i_1}_{j_1 j_2}$ and $\phi^{\lambda_1 i_1}_{j_1 j_2}$ are the phonon amplitudes determined from the solution of the RPA equation, and $\Delta\omega(\lambda_1 i_1, \lambda_2 i_2)$ is the two-phonon pole shift, the explicit form of it is given in ref. [10]. As has been shown in papers [22], this shift should be taken into account calculating the low-lying states. In calculating the GMR the shift is small and it can be neglected.

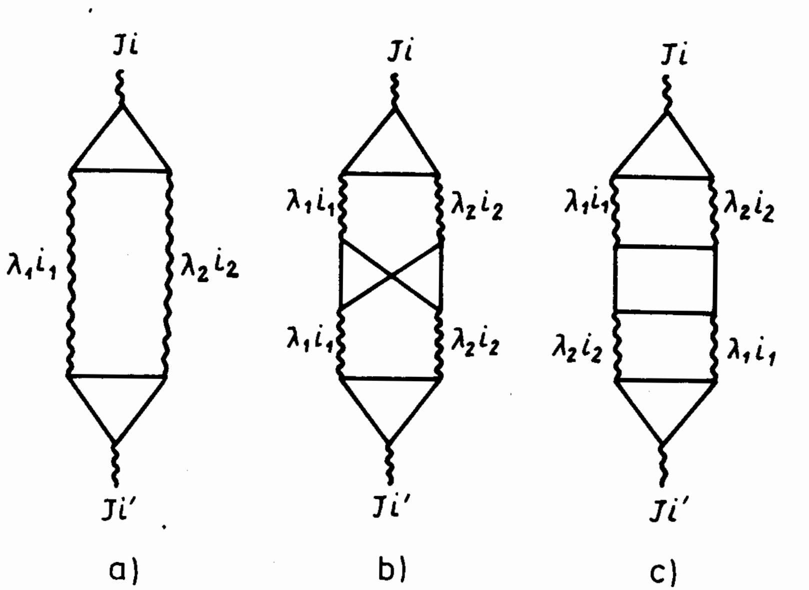
The wave function (1) is normalized as follows:

$$\langle\Psi^*_\nu(JM)\Psi_\nu(JM)\rangle = \sum_i (R_i(J\nu))^2 + 2\sum_{\substack{\lambda_1 i_1\\ \lambda_2 i_2}} (P^{\lambda_1 i_1}_{\lambda_2 i_2}(J\nu))^2 \times \quad (4)$$

$$\times\{1 + \frac{1}{2}K^J(\lambda_1 i_1, \lambda_2 i_2)\} = 1 .$$

Within the QPM the diagrams given in fig.1 (a,b,c) are taken into account in the one-phonon space. The diagrams in figs.1b and 1c correspond to the corrections due to the exact inclusion of the Pauli principle in the two-phonon components of the wave function (1). It is shown in paper [19] that only particular cases of the diagram in fig.1a, given in fig.1d, are taken into account in the calculations within the NFT. Namely, when one of the intermediate phonons is changed by the two-quasiparticle states and strongly collectivized phonons are used as the other phonon. It should be noted that in all modern theoretical calculations allowing for the 2p-2h configurations [15-20] only the diagrams of the type of fig.1a are used for practical calculations (for the discussion of this problem see papers [5,19]).

Consider eq. (2). The rank of the determinant is equal to the number of one-phonon states in the first term of the wave function (1). The factor $\{1 + \frac{1}{2}K^J(\lambda_1 i_1, \lambda_2 i_2)\}$ is the result of the Pauli principle corrections in the two-phonon components of the wave function (1). For the components forbidden strictly by the Pauli principle $K^J = -2$ and the corresponding terms are excluded from the sum in formulae (2) and (4). With $K^J = 0$, the secular equation (2) transforms into the well-known equation



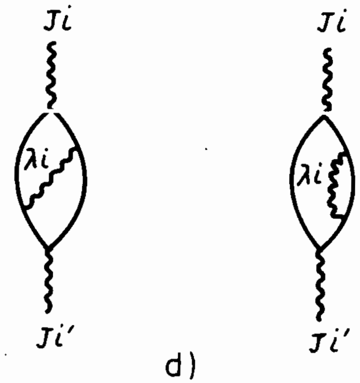


Fig.1. Diagrams included in the QPM (a,b,c) and NFT (c).

used in papers [11-14] for the study of the fragmentation of one-phonon and two-quasiparticle states. For this purpose the GIRES program[23] was used, in which the two-phonon components with two noncollective phonons violating the Pauli principle were excluded in the process of numerical solution of eq.(2) with $K^J = 0$. Under such a procedure, the shift of two-phonon poles, which may be important for some low-lying states, was not taken into account, and a part of the components permitted by the Pauli principle was excluded. Below, by the numerical example, we shall compare the results of an approximate and exact inclusion of the Pauli principle.

The strength function method frequently used in the calculations within the QPM allows one to calculate the strength distribution of any physical quantity averaged over the energy interval Δ without solving eq. (2). In the general case the strength function has the form

$$b(\lambda, \eta) = \frac{1}{\pi} \mathrm{Im} \{ \sum_{ii'} \mathcal{A}_{ii'}(\eta + i\Delta/2) \mathfrak{M}_{Ji} \mathfrak{M}_{Ji'} / \mathcal{F}(\eta + i\Delta/2) \}, \quad (5)$$

where $\mathcal{A}_{ii'}$ are cofactors of the determinant (2) at complex energy values. A concrete form of the matrix elements $\mathfrak{M}_{Ji}$ depends on the process under consideration[9]. In the present paper $\mathfrak{M}_{Ji}$ correspond to the matrix elements of the $E\lambda$-transitions from the ground to the one-phonon states.

The method of choosing the constants of the QPM Hamiltonian is described in papers [9,11-14]. In this paper we use the same set of parameters as in papers [12,14,24].

2. THE RESULTS OF CALCULATION

Now we study the influence of a more exact inclusion of the Pauli principle in the two-phonon components of the wave function (1) as compared to an approximate procedure used within the QPM [10-14]. The strength distributions of the isoscalar giant quadrupole resonance in ^{118}Sn are shown in fig.2. For the calculation of the strength functions $b(E2, \eta)$ with an exact inclusion of the Pauli principle, we have used the function $\mathcal{F}(\eta)$ determined by formula (2) at $\Delta\omega = 0$, as for the GMR the renormalization of two-phonon poles is small[22]. As one can see from fig.2, a more exact inclusion of the Pauli principle somewhat diminishes the $b(E2, \eta)$-value at maximum, whereas the integral strength decreases only by 5% in the interval from 5 to 14 MeV. On the whole, an approximate procedure of elimination of the states forbidden by the Pauli principle, realized in paper [23], is almost equivalent to an exact inclusion of the diagrams 1b and 1c, though it is much simpler from the computational point of view. For the states, which are not strictly forbidden by the Pauli principle, the interaction renormalization due to the Pauli principle corrections turns out to be weak. The neglect of the requirements following from the Pauli principle may lead to the appearance of many spurious two-phonon components in the wave function (1).

Let us consider how strong is the difference of the results of calculations within the QPM, when the diagrams of the type of figs.1a-1b are summed, in comparison with the results of calculations within the NFT, when the diagrams shown in fig.1c are summed. Within the NFT in the diagrams 1a a collective and a noncollective phonons are used as the intermediare phonons

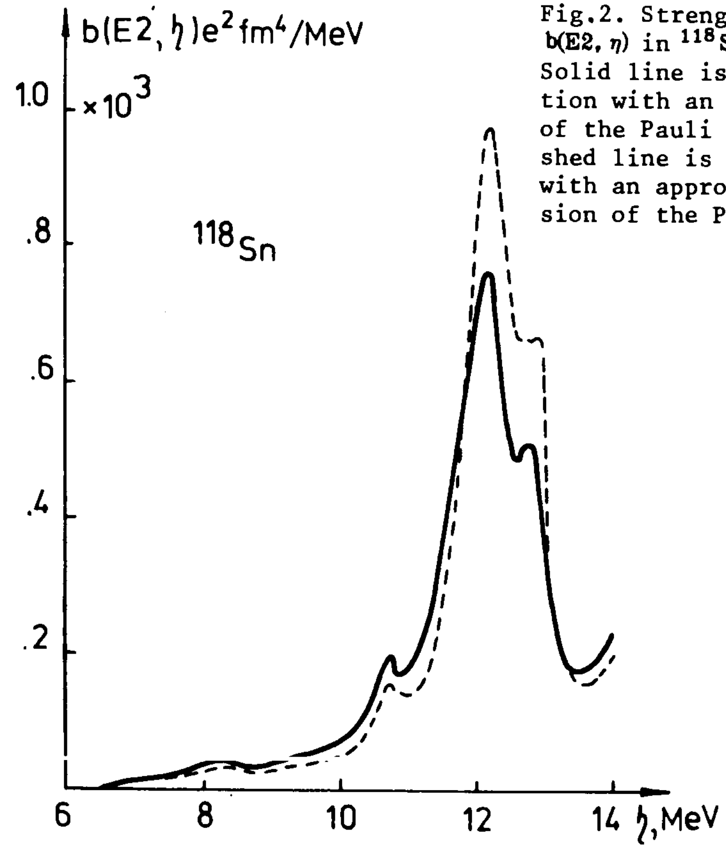
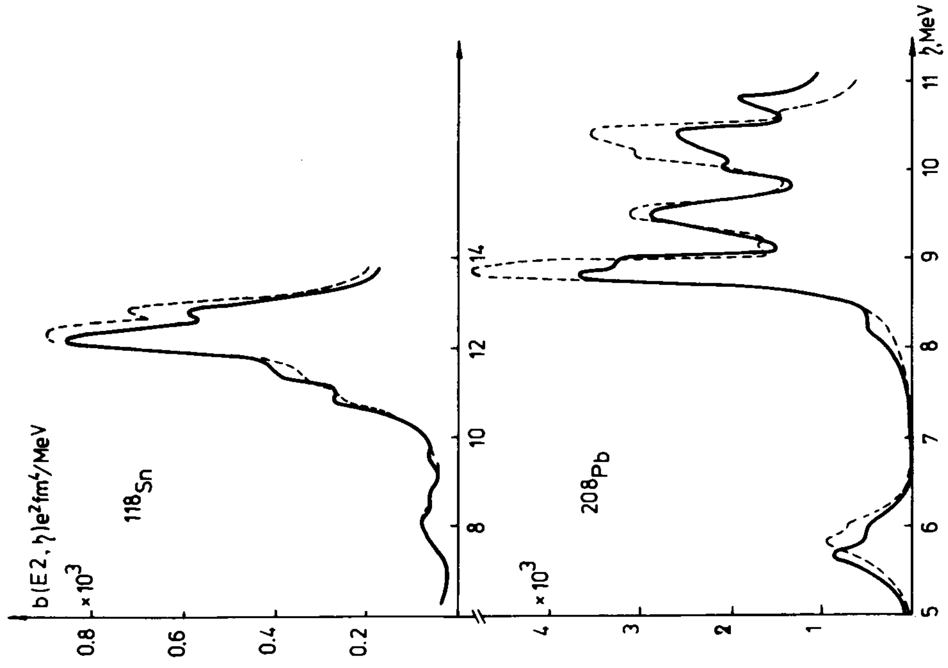


Fig.2. Strength functions $b(E2,\eta)$ in ^{118}Sn (Δ = 0.2 MeV). Solid line is the calculation with an exact inclusion of the Pauli principle, dashed line is the calculation with an approximate inclusion of the Pauli principle.

(the two-quasiparticle state, in fact). The division of phonons into collective and noncollective or weakly collective is somewhat arbitrary. We consider the one-phonon state to be collective if in the normalization of its wave function there are no components giving a more than 50% contribution. The states that do not satisfy this criterion are thought to be weakly collective. The results of calculations within the QPM and NFT are given for the giant isovector dipole resonance in ^{118}Sn (Δ = 0.2 MeV) in fig.3 and for the isoscalar quadrupole resonance in ^{118}Sn (Δ = 0.5 MeV) and ^{208}Pb (Δ = 0.2 MeV) in fig.4. It is seen from these figures that the QPM and NFT provide similar results, though within the QPM calculations the GMR strength is fragmented somewhat stronger. Though the amplitude of peaks obtained with the inclusion of the diagrams 1c is a little larger, on the whole both the calculations give the same gross-structure of the E2-strength distribution. This indicates that the most important diagrams are taken into account within the



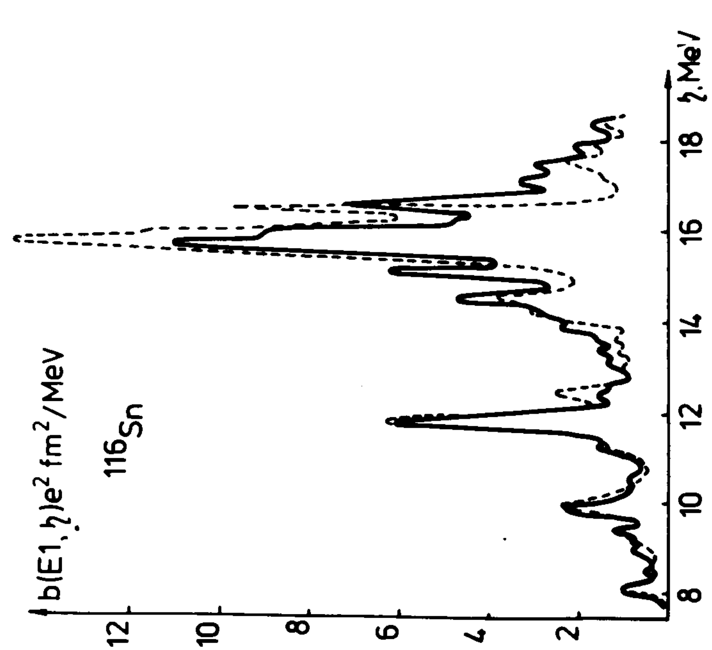


Fig.3. Strength function for the giant dipole resonance in ^{118}Sn. Solid line is the calculation with the diagrams 1a,b,c; dashed line is the calculation with the diagram 1c.

Fig.4. Strength functions for the isoscalar quadrupole resonance in ^{118}Sn and ^{208}Pb. The notation is the same as in fig.3.

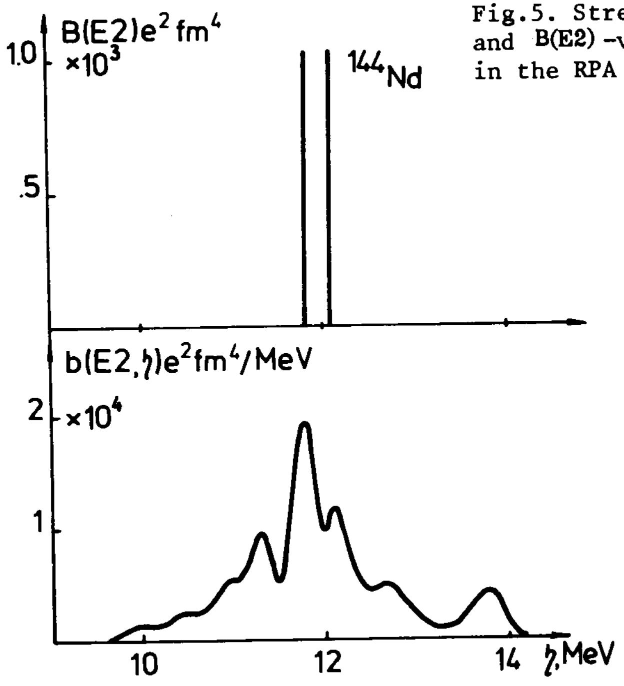


Fig.5. Strength function b(E2) and B(E2)-values calculated in the RPA for ^{144}Nd.

NFT. Note, that the afore-made conclusions remain valid if a 30%-value is taken as a criterion of the phonon collectivity. In this case the values of strength functions change very slightly.

A possibility of making calculations in nuclei with open shells is one of the advantages of the QPM. This is demonstrated in paper/12/ in calculating the total cross sections of the dipole photoabsorption in ^{124}Te and ^{140}Ce. The results of calculations of the strength functions b(E2, η) in ^{144}Nd are presented in fig.5. The RPA calculations, given in this figure, show that the total isoscalar E2 resonance strength is concentrated on two solutions at the excitation energies of about 12 MeV. The coupling with the two-phonon states redistributes the resonance strength in the energy interval from 10 to 14 MeV. This figure clearly demonstrates the appearance of the E2 resonance width due to the fragmentation of one-phonon states. The integral characteristics of the isoscalar giant quadrupole resonances are illustrated in the table. The E2 resonance widths have been calculated by the standard formula for the Gauss distribution (see refs./5,8/). In the nuclei under consideration from 50 to 70% of the isoscalar energy weighted sum rule (EWSR) is exhausted in the E2 resonance region. The calculated energy values are very close in the experimental systematics for the energies of the isoscalar E2 resonance $E_x \sim 65 A^{-1/3}$ MeV. The isoscalar E2 resonance in ^{208}Pb is rather well studied experimentally. However, it is not yet established what part of the model independent EWSR is exhausted in the resonance region. According to the experimental papers/27,28/ on the excitation of the E2 resonance in (α, α′) and (d, d′) in ^{208}Pb, E_x = 10.5-10.9 MeV and (60-80)% of the EWSR is exhausted. Many 2^+ states have been observed in the excitation energy interval 8-12 MeV in the electron scattering on ^{208}Pb/29/. There is a rather strong fragmentation of strength with individual centers of gravity around E_x = 8.9, 10.2, 10.6 MeV. The experimentally measured E2 resonance strength is (29^{+11}_{-8})% of the EWSR. As is seen from fig.4, the calculated strength function in ^{208}Pb also has substructures at energies 8.8, 9.5, 10.4 and 10.8 MeV. However, it should be mentioned that in the calculations with Δ = 0.2 MeV a fine structure of peaks is smeared. The strength function b(E2, η) calculated with Δ = 0.05 MeV is exemplified in fig.6. It is seen from this figure that the quadrupole resonance in ^{208}Pb has a rich fine structure. The E2 resonance gross-structure is due to the coupling of the one-phonon state with the two-phonon states including collective phonons. A fine structure is to a great extent due to the two-phonon states constructed of non-collective phonons. According to the theoretical calculations/14-20/, about 70% of the EWSR is exhausted. Recently, new data on the GMR excitation in ^{208}Pb in the inelastic ^{3}He scattering has been reported in paper/30/. It was observed in these experiments that a hexadecapole resonance exhausting (23-29%) of the EWSR is also localized in the E2 resonance region. For the quadrupole resonance the EWSR is exhausted by (32-50)%. According to our calculations, several 4^+ states exhausting about 18% of

Table

Properties of the giant quadrupole resonances

Nucleus	Experiment				Calculated		
	E_x, MeV	Γ, MeV	EWSR(%)	ref.	E_x, MeV	Γ, MeV	EWSR(%)
^{118}Sn	~12	-	-	/25/	12.1	2.1	51.7
^{144}Nd	-	-	-	-	11.9	2.1	49.4
^{208}Pb	10.9±0.3	2.4±0.4	80	/26/	9.6	1.8	66

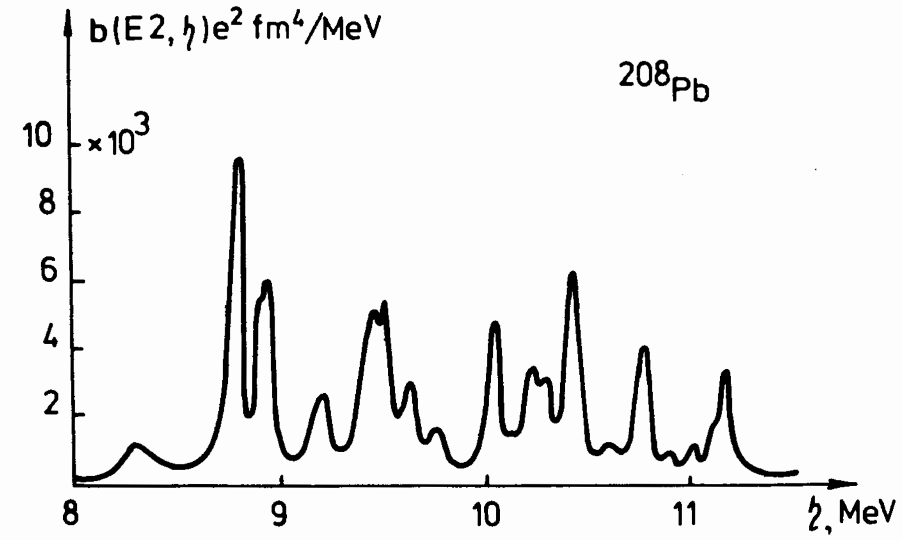


Fig.6. Strength function $b(E2,\eta)$ for ^{208}Pb, calculated with Δ = 0.05 MeV.

the EWSR lie at energies with the center of mass E_x = 10.2 MeV. Close results have been obtained within the NFT /19/. Thus, the experimental data for the E4 resonance are in a fairly good agreement with the theoretical calculations, though the problem of the E2 resonance strength is still open.

CONCLUSION

In the present paper we have demonstrated the possibilities of the QPM in describing the GMR properties in magic and non-magic nuclei. It is shown that the calculations within the NFT and QPM provide close results, though the latter takes into account a wider class of diagrams. Our calculations have also shown that an approximate inclusion of the Pauli principle, widely used within the QPM, turns out to be practically equivalent to an exact inclusion of the Pauli principle for the two-phonon components. In describing the GMR properties various theoretical schemes provide close results, though in some cases there is a considerable difference between the data from various reactions and theoretical calculations.

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REFERENCES

1. Berman B.L., Fultz S.C. Rev.Mod.Phys., 1975, 47, p.713.
2. Speth J., Van der Woude A. Rep.Prog.Phys., 1981, 44, p.719; Goeke K., Speth J. Ann.Rev.Nucl.Part.Sci., 1982, 32, p.65.
3. Soloviev V.G. Nuclear Struct. Dubna Symp., 1968, IAEA, Vienna, 1968, p.101; Соловьев В.Г. Изв. АН СССР, сер.физ., 1971, 35, с.666.
4. Soloviev V.G. Proc.Int.Conf. on Neutron Capture Gamma-Ray Spectroscopy. Reactor Centrum Nederland, Petten, Netherlands, 1975, p.99.
5. Bertsch G.F., Bortignon P.F., Broglia R.A. Rev.Mod.Phys., 1983, vol.55, p.287.
6. Вдовин А.И., Соловьев В.Г., Стоянов Ч. ОИЯИ, Р4-10033, Дубна, 1976.
7. Соловьев В.Г. Теория сложных ядер. "Наука", М., 1971; Soloviev V.G., Malov L.A. Nucl.Phys., 1972, A196, p.433; Соловьев В.Г. ТМФ, 1973, 17, с.90; Вдовин А.И., Соловьев В.Г. ТМФ, 1974, 19, с.275.
8. Вдовин А.И., Кырчев Г., Стоянов Ч. ТМФ, 1974, 21, с.137; Кырчев Г., Соловьев В.Г. ТМФ, 1975, 22, с.255.
9. Соловьев В.Г. ЭЧАЯ, 1978, 9, с.580; Nucleonica, 1979, 23, p.1149; Вдовин А.И., Соловьев В.Г. ЭЧАЯ, 1983, 14, с.237; Воронов В.В., Соловьев В.Г. ЭЧАЯ, 1983, 14, с.1380.
10. Soloviev V.G., Voronov V.V. JINR, E4-83-58, Dubna, 1983.
11. Soloviev V.G., Stoyanov Ch., Vdovin A.I. Nucl.Phys., 1977, A288, p.376.
12. Soloviev V.G., Stoyanov Ch., Voronov V.V. Nucl.Phys., 1978, A304, p.503.
13. Soloviev V.G. Proc. Int.Conf. on Nucl.Struct., Tokyo, 1977, J.Phys.Soc.Jap., 1978, 44, p.323; Soloviev V.G. Proc. Sendai Conf. on Electro- and Photoexcitations. (Ed. by Kawazoe). Tomizawa, Sendai, Japan, p.111; Соловьев В.Г. Труды IV семинара "Электромагнитные взаимодействия ядер при малых и средних энергиях", 1977, с.22.
14. Soloviev V.G., Stoyanov Ch., Voronov V.V. Nucl.Phys., 1983, A399, p.141.
15. Dehesa J.S. et al. Phys.Rev., 1977, vol.C15, p.1858.
16. Bertsch G.F. et al. Phys.Lett., 1979, vol.808, p.161; Broglia R.A., Bortignon P.F. Phys.Lett., 1981, vol.101B, p.135.
17. Adachi S., Yoshida S. Nucl.Phys., 1978, vol.A306, p.53.
18. De Haro R., Krewald S., Speth J. Nucl.Phys., 1982, A388, p.265.
19. Bortignon P.F., Broglia R.A. Nucl.Phys., 1981, vol.A371, p.405.
20. Wambach J., Mishra V.K., Li Chu-Hsia. Nucl.Phys., 1982, vol.A380, p.285.

21. Камерджиев С.П., Целяев В.И. Изв. АН СССР, сер.физ., 1983, т.47, с.917.
22. Соловьев В.Г., Стоянов Ч., Николаева Р. ОИЯИ, Е4-83-166, Дубна, 1983.
23. Пономарев В.Ю., Стоянов Ч., Стоянова О. ОИЯИ, Р4-81-704, Дубна, 1981.
24. Soloviev V.G., Stoyanov Ch., Vdovin A.I. Nucl.Phys., 1980, A342, p.503.
25. Yamagata T. et al. Phys.Rev., 1981, C23, p.937.
26. Bertrand F.E. et al. Phys.Rev., 1980, C22, p.1832.
27. Marty N. et al. Proc.Int.Symp. on Highly Excited States, Jülich, 1975; IPNO PhN-76-03, Orsay, 1976.
28. Morsch H.P. et al. Phys.Rev., 1980, C22, p.489; Phys.Rev. Lett., 1980, 45, p.337.
29. Kühner G. et al. Phys.Lett., 1981, 104B, p.189.
30. Yamagata T. et al. Phys.Lett., 1983, 123B, p.169.

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Нгуен Динь Данг и др. E4-83-680
Описание гигантских мультипольных резонансов
в сферических ядрах

В рамках квазичастично-фононной модели ядра рассчитаны характеристики изоскалярных квадрупольных резонансов в ряде ядер. Проведено сравнение этой модели с теорией ядерных полей. Выяснено влияние поправок, возникающих при точном учете принципа Паули в двухфононных компонентах волновых функций, на характеристики резонансов.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

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Nguyen Dinh Dang et al. E4-83-680
Description of Giant Multipole Resonances
in Spherical Nuclei

The characteristics of the isoscalar quadrupole resonances in some nuclei are calculated within the quasiparticle-phonon nuclear model. This model is compared with the nuclear field theory. The influence of the Pauli principle corrections in the two-phonon components of the wave functions on the resonance characteristics is established.

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

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