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NUCLEAR STRUCTURE INFLUENCE ON THE MISSING OF M1 STRENGTH IN (p, p′) REACTION

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I. Introduction

Excitation of the magnetic dipole (M1) resonance in $^{90-96}$Zr in the (p,p′) reaction at intermediate energies is to be described in this paper. The first experimental results on this subject have been obtained a few years ago[1] and they are rather helpful in clearing up the situation with the M1 resonance missing in heavy nuclei. The problem was the following - no visible M1 strength in nuclei with $A \gtrsim 100$ had been found in the high resolution (e,e′) experiments at low momentum transferred q [2] in the energy region E_x whereas everybody was sure the resonance had to be located. In ^{90}Zr only a few weak 1^+ levels with $\sum B(M1)\uparrow \simeq 0.78\mu_0^2$ have been observed in the region $8.0 \leq E_x \leq 10.0$ MeV and the upper limit for the M1 strength has been given as $\sum B(M1)\uparrow \leq 2.6\,\mu_0^2$ [3] that means only about 20% of the shell model estimation for the pure $\nu(1g_{9/2}^{-1}\,1g_{7/2})$ transition. One of the possible reasons for the (e,e′) experimental failure, as has been pointed out in ref.[4], is the masking of the M1 transitions by the M2 resonance that is located in the same region E_x and excited more intensively than the M1 resonance at q achieved in the (e,e′) scattering.

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In ^{90}Zr this was confirmed in the high resolution (p,p′) reaction with E_p=319 MeV [9]. Recently the M1 resonance has been observed in ^{206}Pb by polarized (γ,γ') reaction[10].

The question that still remains opened is connected with the strength of M1 transitions. Their damping exists though not so strongly as was concluded from the (e,e′) experiments. The experimental cross section of the M1 resonance excitation in the (p,p′) reaction in Zr isotopes is about 30% of the theoretical one calculated for the pure $\nu(1g_{9/2}^{-1}1g_{7/2})$ configuration [7]. It is clear that there are many different reasons for the M1 strength damping. But in any case one has to start with ordinary nuclear structure effects and do his best and only if failed, he would argue about other additional effects and their contribution. From this point of view it is more consistent to calculate directly the cross section of the reaction with microscopic wave function of the resonance than to compare such values as B(M1) or the response function with the experimental ones obtained in the model dependent way. So, we try to fulfil this program in this paper.

2. Quasiparticle-Phonon Model and 1^+ State Properties in Zr Isotopes

The structure of 1^+ levels in $^{90-96}$Zr is calculated here in the quasiparticle-phonon model (QPM) [11,12]. We have two reasons to use this model. First, its Hamiltonian includes pairing interactions which are important in these nuclei. Second, in this approach we can calculate the structure of the levels by taking into account a configuration mixing of 1p-1h with 2p-2h states and thus it is easy to calculate their excitation probabilities in different reactions. There are some weak points of the QPM - it uses a schematic separable particle-hole interaction and restricts single-particle spectrum of the Saxon-Woods potential to only bound and narrow quasibound levels. Recently the excitation of the M1 resonance in ^{90}Zr in the (p,p′) reaction has been calculated in the framework of the finite fermi-system theory (FFST)[13,14] which is free from these short-comings. But neither pairing interaction in the proton system of ^{90}Zr (but only some estimations of its role) nor coupling to the complex configurations was taken into account in refs.[13,14].

The effective particle-hole interaction for 1^+ states in the QPM has the form:

$$V_\sigma(\vec{r}_1,\vec{r}_2) = -\frac{1}{2}\left(\varkappa_0^{(01)} + \vec{\tau}_1\vec{\tau}_2\,\varkappa_1^{(01)}\right) f(r_1)\,f(r_2)\,\vec{\sigma}_1\vec{\sigma}_2\,. \qquad (1)$$

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As for the (p,p′) scattering q -values for $\theta \sim 2°-4°$ are much smaller than under the conditions of the (e,e′) experiments. That is why we find a predominant excitation of states with angular momentum transferred L=0 and suppression of states with $L \geq 1$ in the (p,p′) experiments/5/. Moreover, due to the behaviour of different components of the interaction between the projectile and the target, spin and spin-isospin modes are intensively excited by protons with E_p = 100-300 MeV. As a result, it was just the (p,p′) reaction at intermediate energies to "rediscover" the M1 resonance. In Zr isotopes the resonance is clearly seen as a bump over a background with its energy slightly decreasing with increasing A from 8.9 MeV in ^{90}Zr to 8.6 MeV in ^{96}Zr and width $\Gamma \simeq 1.5$ MeV /7/. In heavier nuclei (^{120,124}Sn, ^{140}Ce) the M1 resonance is not so visibly separated from the background because of the difficulties with subtraction of the tail from the elastic peak and possible L=1 excitations /8/. Nevertheless, the existence of the M1 resonance in heavy nuclei is out of questions now. In ^{90}Zr this was confirmed in the high resolution (p,p′) reaction with E_p=319 MeV /9/. Recently the M1 resonance has been observed in ^{206}Pb by polarized (γ,γ') reaction/10/.

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The radial form factor $f(r)$ is taken in this paper as $f(r) = dU/dr$; $U(r)$ is the central part of the Saxon-Woods potential. Two-quasiparticle states with $\Delta\ell=2$ do not give a contribution to the structure of one-phonon 1^+ excitations if we use only $\sigma\sigma$ -forces (1). But as has been shown in ref./15/ their influence on the M1 resonance properties is negligible.

The parameter of the spin-isospin interaction $\varkappa_1^{(01)}$ is fitted to the experimental location of the M1 resonance and it differs from nucleus to nucleus. As for the spin interaction, it is rather weaker here $(\varkappa_0^{(01)} = 0.1\,\varkappa_1^{(01)})$, because of the results of papers/13,16/ and our own calculations of the properties of the recently discovered low-lying isoscalar 1^+ level with $E_x = 5.846$ MeV in ^{208}Pb.

If we look at the spectrum of the states with $J^\pi = 1^+$ obtained in the one-phonon approximation, we find two 1^+ states with a large value B(M1, $0^+_{g.s.} \to 1^+_i$) in all Zr isotopes (see Table 1). The state with the maximum value B(M1) is located at the experimental energy of the M1 resonance (that was the input information for the choice of $\varkappa_1^{(01)}$), the second state has the energy $E_x \simeq 11$ MeV. The main contribution to the structure of the "resonance" 1^+ state comes from the configuration $\nu(1g_{9/2}^{-1}\,1g_{7/2})$ and to the state with $E_x \simeq 11$ MeV from the configuration $\pi(1g_{9/2}^{-1}\,1g_{7/2})$. The second 1^+ state appears due to the pairing in the proton system. It should be mentioned that a mixture of the neutron and proton configurations $(1g_{9/2}^{-1}\,1g_{7/2})_{1^+}$ is strong enough; this is because of a large value of the $\nu\pi$ -interaction $(\varkappa_{\nu\pi}^{(01)} = \varkappa_0^{(01)} - \varkappa_1^{(01)} = -0.9\,\varkappa_1^{(01)})$. The increasing of $|\varkappa_0^{(01)}|$ leads to decreasing of the mixing.

The contribution of the component $\nu(1g_{9/2}^{-1}\,1g_{7/2})$ to the wave function of the 1^+ state with $E_x \sim 9$ MeV increases with A because a neutron energy gap becomes larger and as a result, the two-quasiparticle state $\nu(1g_{9/2}\,1g_{7/2})$ comes nearer to the M1 resonance location with each two additional neutrons.

One of the advantages of the QPM, as it has been mentioned earlier, is its ability to take into account the coupling of highly excited one-phonon states to two-phonon configurations /11,12/. In this approximation, the 1^+ states are discribed by the wave function:

$$\Psi_\nu(1^+M)=\Big\{\sum_i R_i(1^+\nu)\,Q^+_{1Mi}+\sum_{\substack{\lambda_1 i_1\\ \lambda_2 i_2}} P^{\lambda_2 i_2}_{\lambda_1 i_1}(1^+\nu)\big[Q^+_{\lambda_1\mu_1 i_1}\,Q^+_{\lambda_2\mu_2 i_2}\big]_{1^+M}\Big\}\Psi_0 . \quad (2)$$

In this formula $Q^+_{\lambda\mu i}$ is the phonon operator with momentum λ , its projection μ and root number i ; Ψ_0 is the wave function of phonon vacuum. The interaction between one- and two-phonon states leads to fragmentation of one-phonon state strength over a great num-

Table 1. Energy (E_x), B(M1)↑ value and the main components of the 1^+ state wave function for the states with the maximum B(M1) values in Zr isotopes. For B(M1) the effective gyromagnetic factors $g_s^{eff} = 0.8\,g_s^{free}$ are used.

Nucleus	E_x, MeV	B(M1)↑, μ_0^2	main components (in %)			
			$\nu(1g_{9/2}1g_{7/2})$	$\pi(1g_{9/2}1g_{7/2})$	$\pi(1f_{7/2}1f_{5/2})$	$\nu(2d_{5/2}2d_{3/2})$
^{90}Zr	8.9	4.35	82.8	10.9	4.1	-
	11.0	3.64	11.4	82.4	2.9	-
^{92}Zr	8.8	4.83	86.2	8.3	2.9	0.9
	10.9	3.27	8.6	86.6	2.5	-
^{94}Zr	8.7	5.20	89.2	6.2	2.0	1.2
	10.8	2.89	6.3	90.0	2.0	-
^{96}Zr	8.6	5.44	92.5	4.1	1.2	1.2
	10.7	2.50	4.2	93.2	1.6	-

ber of states with wave function (2) and thus a spreading width of resonance $\Gamma^\downarrow$ appears. The value of $\Gamma^\downarrow$ depends on the strength of the interaction which is calculated in the QPM microscopically and without any new parameters. There is no need in describing all the details of the QPM approach to this problem as they can be found in review/12/, we should only mention that the M1 resonance fragmentation in this approach has been investigated in ref./18/.

Our attention will be concentrated only on the properties of the one-phonon 1^+ state with $E_x \sim 9$ MeV since we identify it with the M1 resonance. Other 1^+ states (there are four one-phonon 1^+ states in ^{90}Zr and five - in $^{92-96}$Zr with $E_x \leqslant 11$ MeV) are located outside the M1 resonance experimental position ($7 < E_x < 10$ MeV) and have a small value of the (p,p′) cross section. Moreover, the strongest of them (1^+ state with $E_x \simeq 11$ MeV) is fragmented over a several MeV region due to the coupling to two-phonon states.

3. Transition Densities of 1^+ States and the Description of the (p,p′) Scattering

The inelastic scattering of 200 MeV proton is described in the DWIA. Nowadays, this approximation is considered reasonable and is widely used for the scattering of particles at intermediate energies. The idea of the approximation is in the substitution of particle--nucleus interaction by interaction of particle with free nucleons neglecting the binding energy of nucleons. For the free t_{NN} -matrix there is a well-known parametrisation in the form of a sum of the Yukawa potentials with parameters fitted to data of the free-nucleons scattering amplitude. In this paper we use the parameters from ref. /19/ obtained for E_p= 210 MeV. If we are going to describe the scattering of an intermediate energy particle at small angles, realistic results will be obtained only with the central component of the t_{NN}-interaction and by treating knock-on exchange terms by means of a pseudopotential. The excitation of the M1 resonance in the (p,p′) reaction was considered under these assumptions in refs./5,14/. In this paper we intend to calculate σ_{th} as accurately as possible, that is why we include the tensor component of the t_{NN} -interaction as well. The knock-on exchange terms are treated here exactly by calculating directly nonlocal form factors with the QPM transition densities. All numerical calculations of the form factors are performed with the computer code from ref./20/ and for the cross section we use the code DWUCK. For the projectile scattering in the nuclear field we use energy and mass dependent optical potential from ref. /21/. Its parameters were fitted to reproduce the elastic cross section of protons and the analysing power for a wide range of nuclei and proton energy.

The transition densities of the 1^+ states were calculated in three approximations: 1) the approximation of free quasiparticles: the M1 resonance is considered to be the pure two-quasiparticle $\nu(1g_{9/2}1g_{7/2})$ excitation; 2) the Tamm-Dancoff approximation (TDA); 3) the random phase approximation (RPA). It makes possible to notice changes in the (p,p′) cross section as the wave function of the resonance becomes more complicated. The local transition densities $\rho^N_{LSJ}(r)$ of the resonance in ^{90}Zr are shown in fig. 1 for these approximations. Both ΔL =0 and ΔL =2 transition densities are presented. It should be mentioned that the absolute value of ρ^N_{011} is larger than that of ρ^N_{211}. Complication of the resonance wave function results in a small shift of ρ^N_{LSJ} maximum inside nucleus, decrease of the amplitude and increase of the width. On the whole, these changes are negligible but as we will see in the following they result in visible changes in the absolute value of the (p,p′) cross section.

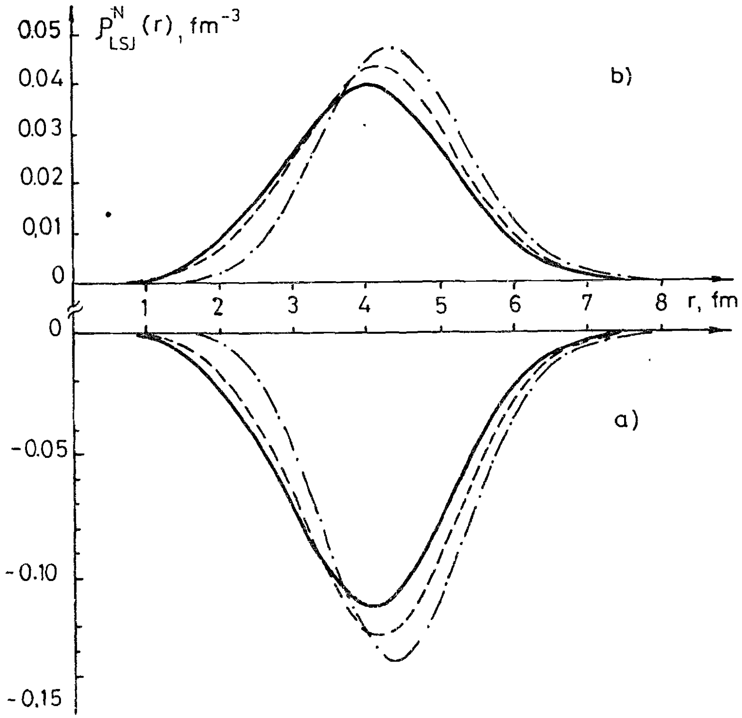

Fig. 1. Transition densities of the M1 resonance in ^{90}Zr calculated under different assumptions of the resonance wave function: a) $\rho^N_{011}(r)$; b) $\rho^N_{211}(r)$. Solid curves are for the RPA, dashed curves are for the TDA, dot-dashed curves are for the pure configuration $\nu(1g_{9/2}1g_{7/2})$.

4. The Results of the (p,p′) Cross Section Calculations

Let us now turn to our calculations of the (p,p′) cross section. We begin here with some methodical aspects of the calculations. In fig. 2 we present the excitation of the M1 resonance in ^{90}Zr obtained with different components of the t_{NN} -interaction, the RPA transition densities being used. It is seen that the tensor components of the t_{NN} -matrix and ΔL =2 transitions are important in describing the cross section behaviour after the first minimum, i.e. $\theta > 10°$. As for $\theta < 10°$, their contribution increases the value

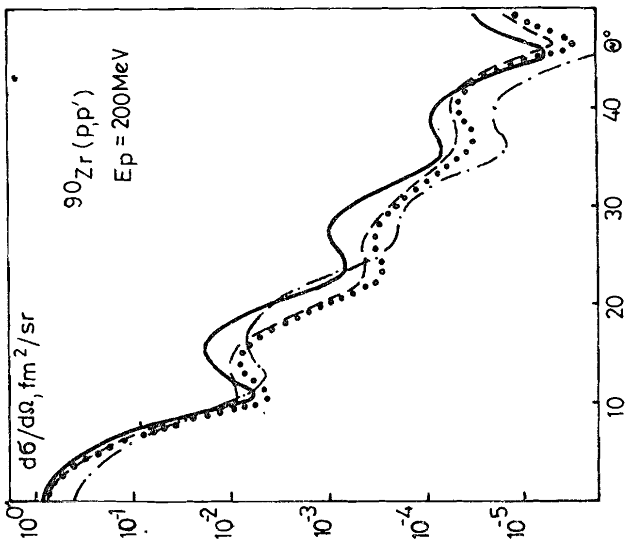

Fig. 2. Excitation of the M1 resonance in ^{90}Zr in the (p,p') reaction: full curve - with the central and tensor components of the t_{NN} -matrix; dashed curve - with only central component of the t_{NN} -matrix; dotted curve - without $\Delta L = 2$ transitions. Dotted-dashed curve is for the excitation of the 1^+ state with E_x=11 MeV (with the central and tensor components).

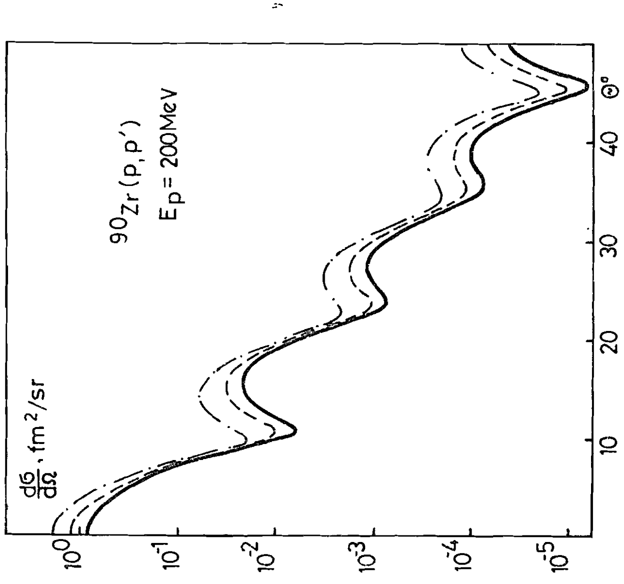

Fig. 3. Excitation of the M1 resonance in ^{90}Zr calculated under different assumptions of the resonance wave function: full curve - with the RPA w.f., dashed curve - with the TDA w.f.; dotted-dashed curve with the w.f. of the pure configuration $\nu(1g_{9/2}\,1g_{7/2})$.

of the (p,p') cross section by about 5-10%. In fig. 2 we also show the excitation of the 1^+ state with $E_x \simeq 11$ MeV. Its cross section is twice as small for forward angles as the one of the M1 resonance though the ratio of their B(M1) values is ~ 1,2 (see table 1). The reason is in that the interaction of the 200 MeV protons with neutrons of nucleus is stronger than with protons of nucleus. It is interesting that the shape of the curves is not very sensitive to either we use RPA or TDA or pure $\nu(1g_{9/2}\,1g_{7/2})$ transition density (fig. 3). The differences are in the absolute value of the cross section. For the pure configuration $\nu(1g_{9/2}\,1g_{7/2})$ the ratio $Q=\sigma_{exp}(\theta)/\sigma_{th}(\theta)$ is got to be equal to 0.32 in ^{90}Zr. This value of Q is close to the one obtained with the code DWBA70 in ref. /7/ with the same wave function of the resonance. For the TDA wave function of the resonance, Q increases up to 0.48 and for the RPA wave function up to 0.64. Just the same situation occurs in other isotopes (see table 2).

Table 2. The quenching factor $Q=\sigma_{exp}(\theta)/\sigma_{th}(\theta)$ obtained in different approximations of the M1 resonance wave function.

Nucleus	$\nu(1g_{9/2}\,1g_{7/2})$	TDA	RPA	$Q^+ + Q^+Q^+$
^{90}Zr	0.32	0.48	0.64	0.79
^{92}Zr	0.25	0.36	0.47	0.56
^{94}Zr	0.34	0.48	0.62	0.75
^{96}Zr	0.34	0.49	0.60	0.68

To compare our results with the experimental angular distributions, we have to turn to fig. 4. Our curves with the RPA wave functions are normalized here to the experimental points by the quenching factor Q from the fourth column of table 2. The shape of the curves in all isotopes is in good agreement with the behaviour of the experimental points. The experimental values $\sigma_{exp}(\theta)$ are systematically larger than $Q\cdot\sigma_{th}(\theta)$ for $\theta \geqslant 8°$; we are sure this is caused by a contribution of excitations with $\Delta L \geqslant 1$ /5/.

The values of Q are close to each other in all isotopes and change similarly with using different approximations of the M1 resonance wave function. The only exception is ^{92}Zr-isotope in which Q is by 25-30% less than in other isotopes for all approximations. This is because the experimental points in ^{92}Zr are lower than in

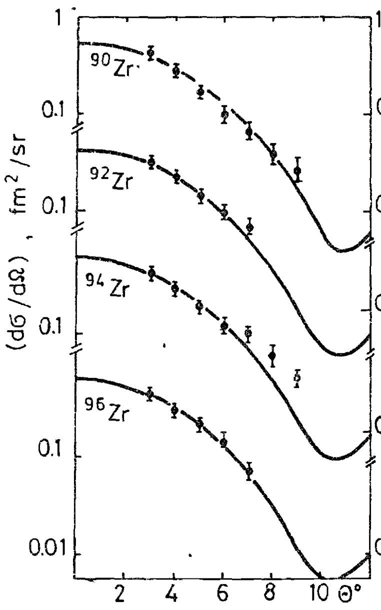

Fig. 4.

Experimental/7/ and theoretical cross sections of the M1 resonance excitation in the (p,p′) reaction. Theoretical curves are obtained with the RPA wave functions and normalised to the experimental data by the factor Q from the fourth column of table 2.

other isotopes. The theoretical calculations do not reproduce this decrease of the cross section and the reason is beyond our understanding. May be a part of the M1 strength was lost with the empirical background extraction.

So, the RPA calculations of the M1 resonance excitation in the (p,p′) reaction give the values about 1.5 - 2.0 times larger than the experimental ones, but they are twice lower than in the calculations with the pure configuration. Thus, nucleon correlations play an important role in the M1 strength damping. Not only an admixture of other two-quasiparticle configurations in the M1 resonance wave function but also ground state correlations are important because we have increase in Q when passing from the TDA to the RPA wave function. The value of Q obtained with our RPA wave function is close to the one in the FFST /14/. There are some differences in explanation of this value. In the QPM the main contribution to the increasing in Q comes from the admixture of proton two-quasiparticle components. In the FFST there is no pairing in the proton system of ^{90}Zr (so, such components as $\pi(1g_{9/2}\,1g_{7/2})$ are missed) and the main admixtures are neutron two-quasiparticle components; as has been pointed out in ref. /13/ an important contribution comes from coupling to the continuum.

The next step to take into account nucleon correlations more consistently is in considering the M1 resonance coupling to two-phonon states; in this approach the resonance is described with the wave function (2). The (p,p′) cross section in this case can be calculated by means of the strength function method /22/. These calculations are analogous to the one for the (e,e′) reaction described

in detail in ref. /23/. Here we use, as usually, the Lorentz weight function with the averaging parameter Δ=0.1 MeV. This value is much less than the experimentally observed width $\Gamma \simeq 1.5$ MeV of the resonance and thus the averaging procedure of the strength function method will not carry a visible discrepancy in the integral probability of the resonance excitation /24/.

As an example, we show in fig. 5b the strength function $b(d\sigma/d\Omega, E_x)$ of the (p,p′) cross section with the excitation of 1^+ states in ^{90}Zr for E_p=200 MeV and θ=3°. To compare, analogous calculations in the RPA are presented in fig. 5a. The centroid of the resonance is not shifted with taking into account coupling to two-phonon states. But the resonance splits into a group of 1^+ states with the wave function (2). Instead of the single RPA-excitation at E_x= 8.9 MeV, which we identify with the M1 resonance, we have in fig. 5b a resonance structure at about the same energy but also a substructure at $\bar{E}_x$=9.5 MeV and a group of weakly excited states which form a low-energy tail of the resonance. The width of the resonance $\Gamma^{\downarrow}$ is much less than the experimental one. Nevertheless, coupling to two-phonon states pushes a part of the M1 strength out the resonance region and leaves 81% of strength of the RPA state with E_x= 8.9 MeV in the region ΔE_x=1.5 MeV. The substructure of the strength function over 10 MeV is mainly due to fragmentation of the RPA-state with E_x = 11 MeV. The same features are obtained in other Zr isotopes.

It should be pointed out that coupling to two-phonon states does not lead to missing of the full M1 strength but does lead to its redistribution over a large number of states (2) with many of them weak and out of the resonance region; so they can be missed in the background extraction. So, due to the coupling we get an additional increase in the factor Q that is presented for this approximation in the last column of table 2. Taking into account our previous comments on ^{92}Zr, we can say that in the (p,p′) reaction at intermediate energy about 70-80% of the M1 strength in Zr isotopes predicted here has been observed. That is the result.

Maybe our calculations underestimate the coupling strength. First, we do not include ground state correlations arising due to the phonon interaction, as has been shown in refs. /25/. Second, in other papers /26,27/ the fragmentation of the M1 resonance in ^{90}Zr is stronger than we have. The coupling in ref. /27/ results in the appearance of the long high-energy tail of the M1 strength distribution and thus a part of the strength will be missed in the background.

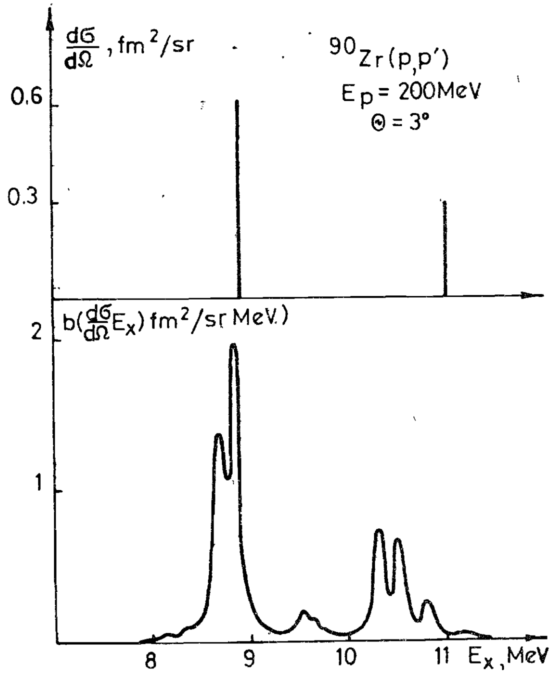

Fig. 5. Excitation of 1^+ states in ^{90}Zr in the (p,p') reaction with $E_p = 200$ MeV and $\theta = 3°$: a) calculations with the RPA wave function; b) strength function $b(d\sigma/d\Omega, E_x)$ calculated with the wave function (2).

5. Last Remarks

The main output of this paper is the conclusion that the nucleon correlations play an important if not a dominant role in the damping of the M1 strength. At least, the well-known effects of nuclear structure without the coupling to Δ -isobar decrease the probability of the M1 resonance excitation in the (p,p') reaction by a factor of 2.0 - 2.2 and reduce the discrepancy between theoretical and experimental results up to 20-30%. The values of Q obtained here are in agreement with the effective gyromagnetic factors $g_s^{eff} = 0.8\, g_s^{free}$ which have been used in the QPM to reproduce experimental results on the M1 and M2 resonance excitation in the (e,e') reaction /4,23/ and magnetic moments of odd nuclei /28/.

The values of Q in the last column of table 2 are apparently the largest among the published ones (see, e.g., refs. /13,14,29,30/). They are most close to the ones calculated in the FFST approach /13,14,30/. Maybe the large value of Q in this paper is caused by a schematic form of the QPM effective interaction. But in any case Q values in the QPM for different processes with M1 and M2 excitation and magnetic moments are in agreement with each other.

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Влияние ядерной структуры на фактор подавления M1-резонанса в (p, p') реакции

Сечения возбуждения M1-резонанса в изотопах $^{90-96}$Zr в неупругом рассеянии протонов с энергией E_p = 200 МэВ рассчитаны в импульсном приближении метода искаженных волн. В расчетах учитывались центральные и тензорные компоненты свободного t_{NN} -взаимодействия падающего протона с нуклонами ядра. Волновая функция M1-резонанса рассчитывалась с сепарабельным эффективным спин-спиновым взаимодействием в приближениях Тамма-Данкова и случайной фазы. Были проведены расчеты, учитывающие взаимодействия с двухфононными конфигурациями в рамках квазичастично-фононной модели ядра. Показано, что фактор подавления вероятности возбуждения M1-резонанса в (p, p')-рассеянии сильно зависит от сложности модельной волновой функции резонанса. Для модельной волновой функции, включающей одно- и двухфононные компоненты, среднее значение фактора подавления равно 0,74.

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Nuclear Structure Influence on the Missing of M1 Strength in (p,p') Reaction

The excitation cross-sections σ_{theor} of the M1-resonance in $^{90-96}$Zr in (p, p')-reaction at E_p = 200 MeV are calculated within the microscopic antisymmetrized distorted wave approximation. The free t_{NN} -interaction of an incident proton with a target nucleus consists of central and tensor parts. The microscopic transition densities are calculated in the framework of the quasiparticle-phonon model. Different approximations are explored for the model wave function of the M1-resonance. It has been found that the quenching factor $Q = \sigma_{exp}/\sigma_{theor}$ is sensitive to the structure of the M1-resonance wave function. When the wave function includes one- and two-phonon components, the average Q - value is equal to 0.74.

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

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