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THE ISOSCALAR SPIN-SPIN INTERACTION WITHIN THE QUASIPARTICLE-PHONON NUCLEAR MODEL

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1. Introduction

The magnetic nuclear excitations have been so far an attractive field for both experimentalists and theorists (see, for example/1/). The impressive achievement in this field was the discovery of the 1^+ - state at $E_x = 5.846$ MeV that turned out to be of isoscalar nature. It should be noted that this state, firstly determined by nuclear resonance fluorescence scattering of linearly polarized photons/2/, has been investigated since then in other reactions, namely, in the inelastic proton scattering at $E_p = 65$ MeV/3/ and 201 MeV/4/, proton pick-up reaction ^{209}Bi (d, ^{3}He) ^{208}Pb/3,5/ and inelastic electron scattering/6,7/. Besides the transition probability $B(M1, 0^+_{g.s.} \dashrightarrow 1^+_{IS}) = 1.6 \pm 1.5\,\mu_N^2$ the data have also shown the value of proton amplitude $(1h_{9/2}\, 1h^{-1}_{11/2})_\pi$ in the structure of the state ($\alpha \geq 0.87$) and the momentum transfer dependence of the measured electron-scattering form factor ($0.4 \leq q_{eff} \leq 1.5$ fm^{-1}).

Among different theoretical calculations for 1^+ - excitations in the nucleus ^{208}Pb, only in two cases /8,9/ the theoretical predictions for the isoscalar 1^+_{IS} - state are in satisfactory agreement with the data (the excitation energy with an accuracy to 300 KeV and the probability $B(M1)\uparrow$ to a factor of about 2) . So, the properties of this state known from experiment can be used to test the possibilities of different theoretical models and to determine some parameters of these models. In ref./10,11/ the strength of the effective isoscalar spin-spin interaction in nuclei has been estimated in the above manner and is found to be weak.

In the present work we consider how the known properties of the 1^+_{IS} - state in ^{208}Pb are reproduced within the quasiparticle-phonon nuclear model (QPM)/12-14/. We also use the existing data for this state to determine the isoscalar spin-spin interaction parameter in the QPM.

2. The structure of the isoscalar 1^+ state in ^{208}Pb

The structure of 1^+- states in ^{208}Pb has been calculated in both the random phase approximation (RPA) and the approximation including the interaction between one- and two- phonon configurations. The structure of $1^\pm$ one-phonon states is determined by spin-spin and spin-quadrupole components of the effective N-N forces used in the QPM/13/.

$$V_\sigma(\vec{r}_1,\vec{r}_2) = -\frac{1}{2}\left(\varkappa_0^{(01)} + \varkappa_1^{(01)}\vec{\tau}_1\vec{\tau}_2\right)R_0(r_1)R_0(r_2)(\vec{\sigma}_1 Y_0)_{1M}(\vec{\sigma}_2 Y_0)^+_{1M} \tag{1}$$
$$-\frac{1}{2}\left(\varkappa_0^{(21)} + \varkappa_1^{(21)}\vec{\tau}_1\vec{\tau}_2\right)R_2(r_1)R_2(r_2)(\vec{\sigma}_1 Y_{2\mu})_{1M}(\vec{\sigma}_2 Y_{2\mu})^+_{1M}.$$

The calculations have been performed with two types of radial form factors of the effective forces $R_\lambda(r)$: a) $R_\lambda(r)= r^\lambda$; b) $R_\lambda(r)=dU/dr$ (U is the central part of the Woods-Saxon potential). It should be noted that a) is rather a traditional variant of spin-spin forces with the constant radial matrix element. The parameters of the single-particle Woods-Saxon potential are taken from parametrization by Chepurnov/15/. But the single-particle energies of the main neutron and proton shells close to the Fermi level, i.e. N=82-126; 126-184 and Z=50-82; 82-126 are taken from ref./16/. In that work, these energies were found by an iterative procedure including quasiparticle-phonon interaction so as to get the best description of the low-lying excited states in ^{207,209}Pb, ^{207}Tl and ^{209}Bi. It should be emphasized that these energies are <u>not</u> identical with the so-called "experimental" single-particle spectrum (see, for example,/17/). The agreement with the experimental spectrum can be obtained with the inclusion of quasiparticle-phonon interaction responsible for fragmentation of single-particle states, which leads to the shift of energy levels and the decrease of their spectroscopic factors compared to the single-particle values. In this sense we have used a "bare" single-particle spectrum, as interpreted in ref./18/. As one will see later, this procedure for finding the single-particle energies is very important for our calculations.

2a) Results of RPA calculations

The effective interaction (1) contains 4 free parameters: $\varkappa_{0,1}^{(01)}$ and $\varkappa_{0,1}^{(21)}$. From the available experimental data, one cannot determine all four constants unambiguously. Nevertheless, since the spin-quadrupole forces influence very weakly the lowest 1^+ one-phonon states in ^{208}Pb the constants $\varkappa_0^{(01)}$ and $\varkappa_1^{(01)}$ can be determined quite accurately from the experimental energies of 1^+_{IS} -level and isovector M1- resonance (1^+_{IV} -level). It should be noted that the M1 -resonance in ^{208}Pb is not well known. The fragmentation of this state is expected to be strong and so far only a part of

its total strength has been observed ($\sum B(M1)\uparrow \sim 7 - 8\ \mu_N^2$ in the interval $7.4 \leqslant E_x \leqslant 7.8$ MeV /1/). We have chosen the value of $\varkappa_1^{(01)}$ in a way to reproduce $E(1^+_{IV}) = 7.8$ MeV having in mind the experimental data for the M1-resonance in ^{206}Pb /19/.

Further, some estimations have been made in order to determine the spin-quadrupole constant. In the case of effective forces with $R_\lambda(r) = dU/dr$ it has been supposed that $|\varkappa_1^{(2\lambda)}| \lesssim |\varkappa_1^{(21)}| < |\varkappa_1^{(01)}|$ (see details in/20/). In the case of $R_\lambda(r) = r^\lambda$ the constant $\varkappa_1^{(21)}$ has been chosen to be the same as in ref./21/. In both cases the constant $\varkappa_0^{(21)}$ is derived from $\varkappa_1^{(21)}$ by λ - and L-independent relation $\varkappa_0^{(\lambda L)}/\varkappa_1^{(\lambda L)}$.

The experimental energy of 1^+_{IS} -level and the above mentioned position of the M1-resonance, i.e. 1^+_{IV} - level, are reproduced with the relation of constants $\varkappa_0^{(\lambda L)}/\varkappa_1^{(\lambda L)} \simeq 0.05-0.1$. The calculated energies and transition probabilities $B(M1,\ 0^+_{g.s.} \to 1^+_i)$ for one-phonon 1^+_{IS}- and 1^+_{IV} - states are shown in tab. 1.

<u>Table 1.</u> The excitation energies (E_x) and $B(M1,0^+_{g.s.} \to 1^+)$ values for two lowest one-phonon 1^+ states in ^{208}Pb calculated with different types of effective forces. The $B(M1)\uparrow$ values are calculated with the effective g_s - factor equal to $0.8\ g_s^{free}$.

$R_\lambda(r)$	$\varkappa_0^{(\lambda L)}/\varkappa_1^{(\lambda L)}$	1^+_{IS} - state		1^+_{IV}- state (M1-resonance)	
		E_x, MeV	$B(M1)\ \mu_N^2$	E_x, MeV	$B(M1)\ \mu_N^2$
dU/dr	1/20	5.84	0.99	7.82	19.6
	1/20	6.02	1.39	7.85	19.2
r^λ	1/10	5.82	1.48	7.87	19.1

The value $B(M1,\ 0^+_{g.s.} \to 1^+_{IS})$ calculated with the g -factors for free nucleons (g_s^{free}) overestimates the experimental value by a factor of 2.0 - 2.5 and the agreement within the experimental uncertainty can be obtained with standard values $g_s^{eff} = g_s^{free} \times 0.8$. The main components of the wave function for one-phonon state $|1^+_{IS}\rangle$ are nearly the same from the calculations with two types of effective forces. The amplitude of proton component $(1h_{9/2}\,1h^{-1}_{11/2})_\pi$ is about 0.84-0.86 and is close to the experimental value extracted from reaction ^{209}Bi(d, ^{3}He) ^{208}Pb. Contribution of the particle-hole component with $\Delta l = 2$ generated by spin-quadrupole interaction is of an order of 0.01%. In the calculations with $R_\lambda(r)=dU/dr$ the components with $\Delta n=1$ are of an order of 0.1%, but in calculations with $R_\lambda(r)=r^\lambda$ their contribution is as small as the components with $\Delta l=2$.

The correct choice of spin-orbital splitting of the $1h_\pi$ and $1i_\nu$ shells plays a vital role in our calculations. Suffice it to say that with the single particle spectrum calculated with the parameters of Chepurnov /15/ one cannot reproduce both the energy and transition probability to the ground state for 1^+_{IS}- level. The experimental values of $\Delta\varepsilon_{s.o.}(1h_\pi)$ and $\Delta\varepsilon_{s.o}(1i_\nu)$, values used in our calculations and those calculated with the parameters of Chepurnov are shown in tab. 2. It should be noted that the single-particle spectra used in the calculations of other works, where the properties of the 1^+_{IS} - state are reproduced satisfactorily, always have the $\Delta\varepsilon_{s.o.}(1h_\pi)$ and $\Delta\varepsilon_{s.o}(1i_\nu)$ values very close to the experimental ones (see also tab.2).

Table 2. The spin-orbital splitting values $\Delta\varepsilon_{s.o.}$(MeV) of the $1h_\pi$ and $1i_\nu$ -shells in ^{208}Pb for different single-particle spectra.

$\Delta\varepsilon_{s.o.}$	exper. /17/	Present work (see /16/)	Woods-Saxon pot. from /15/	Ref. /8/	Ref. /9/
$(1h_{9/2}1h^{-1}_{11/2})_\pi$	5.61	5.31	5.81	5.60	5.57
$(1i_{11/2}1i^{-1}_{13/2})_\nu$	5.88	6.05	6.0	5.86	5.85

2b) Interaction with two-phonon configurations

A detailed description of the QPM formalism with the inclusion of interaction between one- and two-phonon states can be found in reviews /14/ whereas the fragmentation of magnetic dipole resonance has been investigated in the work /22/. In contrast with these works instead of using the method of strength functions we have calculated the structure for each 1^+-state. Since the interaction with two-phonon states decreases the energy of 1^+_{IS} - level by about 150 KeV the calculations have been performed with the renormalized constant $\varkappa_0^{(01)}$ which gives the energy of one-phonon isoscalar $1^\pm$ state equal to 6.02 MeV (see tabl.1). The inclusion of interaction with two-phonon states into calculations reduces the calculated energy of 1^+_{IS} -level to the experimental value $E_x(1^+_{IS})$.

We have taken into account the interaction between 1^+_{IS} and 1^+_{IV} - one-phonon states and 325 two-phonon ones with the energy not greater than 15 MeV. The density distribution of two-phonon states is shown in the upper part of fig. 1.

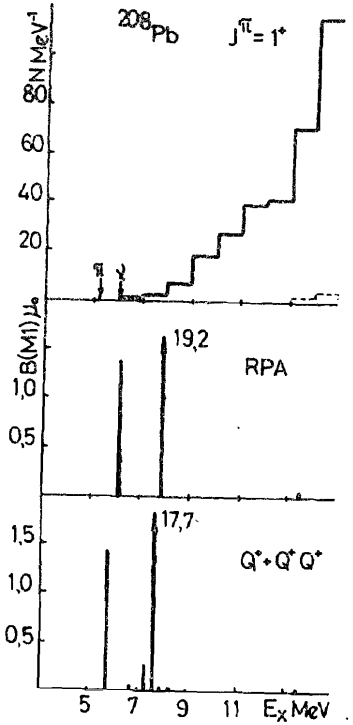

Fig.1. The M1 resonance in ^{208}Pb. The histogram of the number of two-phonon states in the energy interval of 1 MeV (the positions of the 1p - 1 h states $(1i_{11/2}1i^{-1}_{13/2})_\nu$ and $(1h_{9/2}1h^{-1}_{11/2})_\pi$ are indicated by arrows) is shown in the upper part of the figure. The results of calculations in the RPA and with the inclusion of interaction between one- and two-phonon states are shown in the middle and lower parts of the figure respectively.

Fig.1 also shows the distributions of the transition probabilities $B(M1, 0^+_{g.s.} \rightarrow 1^+_i)$ calculated in the RPA (the middle part of Fig.1) and with the inclusion of interaction with two-phonon configurations (the lower part).

The interaction with two-phonon states influences very weakly the 1^+_{IS}-state. The two-phonon part of the wave function for this state does not exceed some percent and the one-phonon component $Q^+(1^+_{IS})\Psi_0$ is around 97%. It should also be noted that the fragmentation of the M1 - resonance is, by the results of our calculations rather weak (see Fig.1). This can be explained, firstly, by the small density of two-phonon states in the energy region of 7-8 MeV, and secondly, by the weak interaction between one-phonon states and two-phonon ones. The maximum matrix elements of this interaction are about 0.3 MeV (note that these matrix elements are calculated in the QPM microscopically /12,14/). The results of other theoretical models have shown that this fragmentation of the M1-resonance is quite stronger /23/. The experimental data (with large uncertainty so far) have shown also that this fragmentation is strong/1,4/.

3. The excitation of the 1^+_{IS} state in ^{208}Pb by inelastic electron and proton scattering

In the previous paragraph we have considered the structure of 1^+_{IS} - state calculated in different approximations within the QPM. Now, we will show how the cross-sections of inelastic electron and proton scattering from ^{208}Pb with excitation of the 1^+_{IS} - state can be described with the model wave functions for this state calculated in the QPM. Since the interaction with two-phonon states influences weakly the 1^+_{IS}- state, all the calculations have been performed with one-phonon wave functions. However, the interaction constants $\varkappa^{(\lambda L)}_{0,1}$ have also been chosen the same as in the "anharmonic" case, i.e. when the energy of one-phonon 1^+_{IS} - state is equal to 6.02 MeV (see tab.1).

The form factor for inelastic electron scattering from ^{208}Pb with excitation of the 1^+_{IS} - state $|F_T|^2$, calculated in the DWBA and the corresponding experimental data from /7/ are shown in Fig. 2. The calculations have been performed with two types of effective interaction. As one can see from Fig. 2, the results of calculation with $R_\lambda(r) = dU/dr$ describe the data quite well in the interval $q_{eff} < 1\ fm^{-1}$. The larger value of q_{eff}, the poorer agreement between theory and experiment, but it should be emphasized that the experimental uncertainty in this region is also larger.

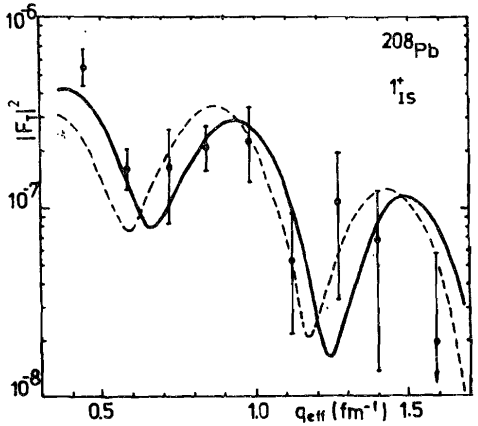

Fig.2. The form factor $|F_T|^2$ of inelastic electron scattering with excitation of the 1^+_{IS} -state in ^{208}Pb. The experimental data are taken from/7/. The solid line is the calculations with the forces dU/dr; the dashed line, with the forces $R_\lambda(r) = r^\lambda$, $g_s^{eff} = 0.8\ g_s^{free}$.

The results of calculation with $R(r) = r^\lambda$ describe the data poorer. This difference comes from the small components with $\Delta n = 1$ in the one-phonon part of the wave function, which influence strongly the behaviour of the current transition densities $\rho_{11}(r)$, especially, in the interior of the nucleus. One can learn about the character of such differences from Fig. 3 where the densities $\rho_{11}(r)$ of one-phonon 1^+_{IS} - and 1^+_{IV} -states are shown. The current transition density of the M1-resonance is changing stronger than that of the 1^+_{IS} -state and the calculations with $R_\lambda(r) = dU/dr$ give a stronger convectional component of $\rho_{11}(r)$.

Note the ambiguity in the extraction of B(M1) -values from the (e,e')-data. The calculations with $R_\lambda(r) = r^\lambda$ give the B(M1)-value greater than that from calculations with $R_\lambda(r) = dU/dr$ when the situation for the form factor $|F_T|^2$ is opposite. If one renormalizes g_s^{eff} by the experimental data for $|F_T|^2$ the B(M1) -value is increased substantially, and for the case $R_\lambda(r) = r^\lambda$ it will go beyond the limits of the experimental uncertainty reported in /2/. So, not surprisingly, value of

$B(M1, 0^+_{gs} \rightarrow 1^+_{IS})$ extracted from the (e,e')-data/7/ turns out to be equal to $1.01 \pm 0.08 \mu_N^2$.

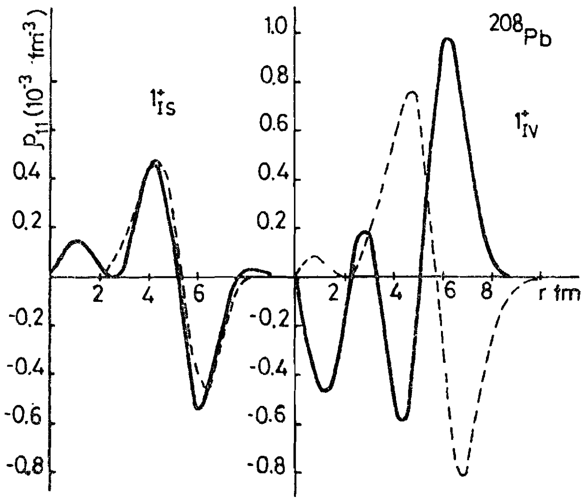

Fig.3.The current transition densities $\rho_{11}(r)$ of the 1^+_{IS} - and 1^+_{IV}- one-phonon states in ^{208}Pb. The solid line is the calculation with $R_\lambda(r) = dU/dr$, the dashed line with $R_\lambda(r) = r^\lambda$.

The calculations of the (p,p') cross-section at $E_p = 201$ MeV have been performed in the distorted wave impulse approximation (DWIA) with the computer code written by F.A.Gareev and S.N.Ershov /24/. The t_{NN} - interaction matrix of free nucleons has been taken as a sum of Yukawa terms as described in/25/. Along with the central components, the tensor components of the t_{NN} -matrix have been included into calculations. The knock-on exchange effects have been taken into account exactly by a nonlocal form factor calculated with one-phonon transition densities. The mass and energy dependent optical potential parameters are obtained from the experimental data of elastic cross-sections and analyzing-power measurements/26/.

The results of calculations with two types of effective forces and the experimental data /4/ are shown in Fig.4. The absolute values of calculated cross-sections overestimate the data by factors of 1.4 (for $R_\lambda(r) = r^\lambda$) and 1.1 (for $R_\lambda(r) = dU/dr$).

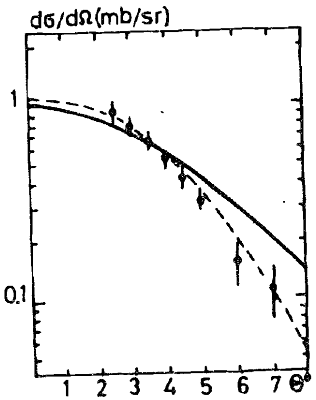

Fig.4.The cross-section of inelastic proton scattering from ^{208}Pb with excitation of the 1^+_{IS}-state (E_p=201 MeV).The experimental data are taken from/4/. The solid line is the calculation with $R_\lambda(r)$=dU/dr, the dashed line with $R_\lambda(r) = r^\lambda$. The absolute values of the calculated cross-sections are normalized to the data.

But the calculation with $R_\lambda(r) = r^\lambda$ gives a much better fit to the (p,p')-angular distribution than the calculation with $R_\lambda(r) = dU/dr$ and it remains nonunderstandable from our point of view. Note, that in the previous QPM-calculations for the (p,p') cross section with the excitation of M1-resonance in Zr isotopes /27/ the angular distributions of outgoing protons have been reproduced quite well. It should also be noted that in the calculations performed within the theory of finite Fermi-systems/28/ the theoretical (p,p') cross section of excitation of the 1^+_{IS}- state in ^{208}Pb falls with scattering angle θ steeper than the experimental one and underestimates it by a factor of two at $\theta = 0^\circ$.

4. Conclusions

In conclusion we would like to emphasize the main results of the present work.

Firstly, the isoscalar spin-spin interaction turns out to be very weak within the QPM. So, the schematic separable interaction used in the QPM also has this important property as the more realistic effective NN-interactions/8,11/.

Secondly, the interaction with more complex configurations influences very weakly the 1^+_{IS} -state and the contribution of the 1p-1h configurations are dominating in the 1^+_{IS} -state wave function.

This conclusion, to a certain degree, may be a model dependent one. Nevertheless, the same result has been obtained in ref.[29]

Thirdly, the empirical values of effective g_s -factors that reproduce the experimental data for inelastic electron scattering form factor and the quenching factor Q for (p,p') cross section with excitation of the 1^+_{IS} -state are consistent with each other within the accuracy of the QPM. It seems that the quenching of the isovector $M\lambda$-strength (see,[20, 27, 30]) is somewhat stronger than the isoscalar one. But in our calculations the difference is not so strong and obvious. The value of Q depends on the effective NN-forces to some extent and the calculations with more realistic forces are highly desirable.

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Дао Тиен Кхоа, Пономарев В.Ю., Вдовин А.И. E4-86-198
Изоскалярное спин-спиновое взаимодействие
в квазичастично-фононной модели

По экспериментальным данным об изоскалярном 1^+-состоянии /E_x = = 5,846 МэВ/ ядра ^{208}Pb определена константа изоскалярного спин-спинового взаимодействия квазичастично-фононной модели ядра /КФМ/. Изоскалярное спин-спиновое взаимодействие оказалось на порядок слабее изовекторного. Рассчитаны сечения /e,e'/- и /p,p'/-рассеяния с возбуждением изоскалярного 1^+-состояния. В целом КФМ удовлетворительно описывает поведение /e,e'/-сечения при $q_{eff} \leq 1{,}0$ фм$^{-1}$ и воспроизводит его абсолютную величину при эффективных спиновых гиромагнитных факторах на 20% меньше, чем у свободных нуклонов. Поведение сечения /p,p'/-рассеяния при E_p=201 МэВ как функции угла рассеяния описывается хуже. Его абсолютная величина в ~ 1,4 раза превосходит экспериментальную, что согласуется с фактором подавления /e,e'/-сечения. Взаимодействие с двухфононными состояниями очень слабо влияет на изоскалярный 1^+-уровень.

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The Isoscalar Spin-Spin Interaction within the
Quasiparticle-Phonon Nuclear Model

The isoscalar spin-spin interaction constant in the quasiparticle-phonon nuclear model (QPM) has been determined from the available experimental data for the isoscalar 1^+ state (E_x=5.846 MeV) in ^{208}Pb. The isoscalar spin-spin interaction turns out to be weaker than the isovector one by an order of magnitude. The cross-sections of (e,e') and (p,p') reactions with the excitation of this 1^+ - state have been calculated. The QPM gives a good description of the behaviour of (e,e')- cross section at $q_{eff} < 1.0$ fm^{-1} and reproduces absolute value of this cross-section with the effective g_s-factors weaker than the g_s-factors for free nucleon by 20%. The description of the (p,p')- angular distribution of 201 MeV photon inelastic scattering is poorer. The absolute value of the calculated (p,p') cross section overestimates the experimental data by a factor of about 1.4. This is consistent with the quenching factor for (e,e') cross section. The interaction with two-phonon configurations influences very weakly the isoscalar 1^+ level.

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

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