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ANALYSIS OF THE NEUTRON ENERGY SPECTRA FROM THE ^{208}Pb (p, n) ^{208}Bi REACTION AT Ep = 200 MeV

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Introduction

In recent years the (p,n) reactions at intermediate proton energies ($E_p \gtrsim 100$ MeV) turned out to be fruitful for the study of charge-exchange excitations in nuclei, especially the spin-flip ones. Thus a new class of giant charge-exchange resonances has been discovered, in particular, the Gamow-Teller resonance (GTR) in a wide range of nuclei (see, e.g., refs.[1-4]) has been investigated. A reliable evidence was obtained for the quenching of the integral strength of low energy spin-isospin transitions with a small transferred momentum q .

The discussion of the physical nature of this effect arose the question about the influence of non-nucleon degrees of freedom (baryon resonances [5]), mesonic exchange currents and multipair excitations[6,7]. Unfortunately, quantitative estimates of the contributions of these mechanisms to the quenching of spin-isospin transitions are so far uncertain.

On the other hand, quantitative estimates on the quenching effect in the continuous spectrum region cannot unumbiguously be obtained only from the experimental data on the inclusive neutron energy spectra since there are no criteria of extracting in a model independent way the contribution of excitation of a certain multipolarity from the others (to separate the resonance from the background). During the last five years the quenching effect has changed almost by a factor of two (from $\approx 30\%$ of the sum rule 3 (N-Z) in the early papers[1-3] up to 50-65% in the last ones[4,8]). This is due to the progress in microscopic calculations in the framework of the distorted wave impulse approximation (DWIA) and to the development of the model for calculating the background in the GTR region. The first qualitative estimates were performed for ^{48}Ca and ^{90}Zr in papers[9] where the "background" was related to the particle-hole transitions with $L > 0$ though without taking into account the effective interactions. A further development of this model is presented for ^{90}Zr in ref.[10]. Calculations with the effective Skyrme interactions have recently been performed for ^{90}Zr in ref.[11]. We have developed a microscopic model for calculating the neutron energy spectra in the framework of DWIA and using the theory of the finite Fermi-system (TFFS). The details of this approach are presented in refs.[12,13]. In the present paper we describe the results of calculations for the ^{208}Pb (p,n) ^{208}Bi reaction at $E_p = 200$ MeV.

The outline of calculations

A microscopic calculation of the neutron spectra is based on the following assumptions:

1) The reaction cross section at relatively small excitation energies of a target nucleus ($E_x < E_p/2$) is mainly determined by the one-step direct mechanism[14] and therefore it can be described in the framework of DWIA;

2) As an interaction of the incident outgoing nucleon with nucleons of the target-nucleus one uses the free NN t-matrix parametrized in a simple form (the sum of Yukawa potentials with different radii) with the parameters taken from the fitting of experimental data on NN scattering amplitude[15]. The spin-orbital and tensor components of the t-matrix are neglected since we are interested in the scattering at small angles where the contribution of these components to the total cross section is small. This is supported by the calculations with pure ph-configurations[3,13]. The neutron knock-on exchange channel is taken into account in the "pseudopotential" approximation[16];

3) The contributions of all particle-hole transitions with the orbital momentum transfer $0 \leq L \leq 3$ and spin $S = 0$ and 1 ($J^\pi = 0^+, 1^+, 0^-, 1^-, \ldots, 4^-$) are taken into account. The calculations performed in ref.[13] have shown that the differential cross sections for higher multipolarities ($L > 3$) are negligibly small especially at small angles. The bound states and resonances were eliminated in the strength functions calculated for the simple charge-exchange multipole fields of the type[17]

$$V^o_{JLS} = [(2L+1)!!/q^L]\, j_L(qr)[\sigma^S_x Y_L]^J \tau_\mp , \qquad (1)$$

where q is the transferred momentum. The RPA transition densities for each state (for the details see refs.[12,13,17]) were used to calculate differential cross sections. In the continuum region the transition densities contain the total multipole strength in the vicinity of the separated resonance (or for the given energy interval) that allows one to include the contributions from nonresonance excitations to the reaction cross section. Thus, the complete multipole strength (sum rule) was practically exhausted in our calculations.

4) Neutron spectra for a given angle θ were found by summing all the calculated differential cross sections folded with the Breit-Wigner distributions to simulate the spreading widths.

The structure calculations within the TFFS has been discussed in refs.[12,13,17]. We shall emphasize here only some specific features.

The strength functions (and transition densities) were calculated with a complete particle-hole basis including the continuous spectrum; this allows one to obtain the transition strength distributions over a wide excitation energy interval and to describe correctly the sum rules. In the spin-isospin channel (that dominates in the reaction considered) the TFFS interaction was used, that involves both the short-range repulsion with the Landau-Migdal parameter $g'=1.1$ (G'_o =330 MeV fm^3) and the one-pion attraction amplitude. The latter is renormalized by the factor $(e^\pi_q[\sigma\tau])^2$ and contains the contribution of the Δ -isobar-hole virtual excitations to the pion self-energy. The factor $e^\pi_q[\sigma\tau]$ is assumed to be equal to the local charge $e_q[\sigma\tau]$ of quasiparticles with respect to the external $\sigma\tau$ -field. In the approximations employed the (p,n) reaction is considered as a result of action on target of the external field obtained by folding the t-matrix with the distorted waves. According to TFFS the $\sigma\tau$ part of this field should be multiplied by the local charge $e_q[\sigma\tau]$. This leads to the decrease in cross sections for the spin-flip transitions due to the factor $e^2_q[\sigma\tau]$. The main goal of the present paper is to elucidate how the neutron spectra at small angles will be reproduced by taking account of this factor and whether it corresponds to the earlier estimates[18]. In the isovector $\tau\tau'$ channel for the structure calculations of natural parity excitations we use the effective density dependent NN interaction satisfying the consistency condition between the isovector mean field potential and the isovector density. No renormalization of the t-matrix in this channel was introduced since the relevant local charge of quasiparticles equals unity which results from the conservation laws[18]. Distorted waves necessary for the calculation were generated in the optical potential whose parameters were taken from ref.[19].

Results and discussion

The calculations were performed using the single-particle Saxon-Woods potential with the parameters chosen so as to describe the experimental single-particle energies and rms radii known for ^{208}Pb[17]. The strength functions of charge-exchange excitations in this nucleus by the fields (1) have been presented in refs.[17]. The total set of bound and resonance states were eliminated from strength

Table 1. Bound and resonance states in ^{208}Bi included into calculation of the differential cross sections and neutron energy spectra for the (p,n) reaction at Ep=200MeV. Transition matrix elements M^2_{0J} are calculated for the external fields $V^{o}_{JLS} = r^L[\sigma^S \times Y_L]^J \tau_-$ with $e_q[\sigma\tau] = 1$, while in calculating $d\sigma/d\Omega$ $e_q[\sigma\tau]$ =0.8 was used.

J^π	(LS)	ω_R (MeV)	M^2_{0J} (fm^{2L})	$d\sigma/d\Omega$ (mb/sr) $\theta = 0^\circ$	2.5°	4.5°
3^+	(21)	4.59	$2\ 10^2$	0.13	0.10	0.11
3^+	(21)	5.17	$1.1\ 10^2$	0.07	0.05	0.06
1^+	(01)	5.40	5.10^{-2}	0.96	0.60	0.21
3^+	(21)	5.49	$2.4\ 10^2$	0.15	0.11	0.13
3^+	(21)	5.96	$6.3\ 10^1$	0.05	0.04	0.04
2^-	(11)	6.05	$1.3\ 10^1$	0.31	1.22	1.67
1^+	(01)	6.08	$3.3\ 10^{-3}$	0.16	0.01	0.01
1^+	(01)	7.02	$2.5\ 10^{-2}$	0.60	0.40	0.20
3^+	(21)	7.50	$7.3\ 10^2$	0.46	0.34	0.38
1^+	(01)	7.52	$2.7\ 10^{-2}$	0.66	0.41	0.21
3^+	(21)	8.20	$6.4\ 10^2$	0.38	0.27	0.31
3^+	(21)	9.05	$6\ 10^2$	0.38	0.26	0.29
3^+	(21)	9.85	$6\ 10^2$	0.40	0.28	0.30
1^+	(01)	11.0	0.64	16.5	7.9	3.0
2^+	(21)	14.2	$1.4\ 10^3$	0.39	0.32	0.63
3^+	(21)	15.0	$3.2\ 10^3$	2.43	1.60	1.60
2^-	(31)	18.0	$3.3\ 10^5$	0.02	0.67	1.50
0^+	(00)	18.8	3.18	18.1	12.8	5.95
1^+	(01)	19.2	5.87	171.6	114.4	40.4
2^-	(11)	20.6	$3.2\ 10^2$	0.72	20.0	32.8
1^+	(01)	22.1	0.9	18.2	12.4	5.1
2^-	(11)	23.2	$2.8\ 10^2$	4.67	21.9	33.5
1^+	(01)	24.1	0.6	11.0	7.5	3.2
3^+	(21)	25.2	$2.7\ 10^4$	14.6	11.1	12.0
1^-	(10)	25.6	$3.5\ 10^2$	4.85	4.79	11.4
0^-	(11)	28.0	$1.3\ 10^2$	2.29	8.44	12.7
4^-	(31)	28.5	$1.7\ 10^6$	0.26	0.34	0.45
1^-	(11)	28.7	$3.4\ 10^2$	13.3	29.3	38.2
1^+	(01)	30.2	0.8	11.0	8.1	4.1
3^-	(31)	33.5	$8\ 10^5$	0.11	0.11	0.15
1^+	(21)	35.2	$1.2\ 10^4$	3.34	4.08	6.09
2^+	(21)	35.5	$1.5\ 10^4$	5.15	5.71	7.81
			Σ =	303.2	275.6	224.5

functions and used for constructing neutron spectra in the excitation energy region $E_x \lesssim$ 30 MeV is shown in table 1. Each state is specified by the total momentum and parity J^π and the asymptotic quantum number (LS). The excitation energies ω_R are given with respect to the ground state of ^{208}Pb and thus coincide with $-Q$ for the (p,n) reaction (in ^{208}Bi $E_x \approx \omega_R - 3.65$ MeV). The table presents the matrix elements of charge-exchange transitions as well as the differential cross sections of the (p,n) reaction at E_p =200 MeV. The list of discrete states (in the region of $\omega_R < 7.5$ MeV), given in table 1, includes only those excitations that give more or less noticeable contribution to the reaction cross section at small angles. All the remaining states may form a very weak background in the low-energy region.

One can easily see from table 1 that the total strength of the Gamow-Teller transitions in the considered region is $\Sigma M^2_{GT} = 4\pi \Sigma M^2_{01} \approx 112$, i.e., $\approx$ 85% of the sum rule 3(N-Z) is exhausted. As has been shown in ref.[13] the strength function of these transitions has a smoothly decreasing behaviour above the energy $\omega \gtrsim$ 40 MeV. This implies that the missed transition strength is distributed in a structureless way in the neutron spectra above $-Q \gtrsim$ 40 MeV.

The structure calculations have shown that $\approx$ 91% of the sum rule (N-Z) for the Fermi transitions is exhausted by the isobaric analog 0^+ state (IAS) for which $M^2_F = 4\pi M^2_{00} \approx 40$. An essential concentration of transition strength in one resonance is also typical for the 0^- and 1^- excitations whereas the spin-dipole 2^- transition strength is considerably fragmented. The fragmentation increases with multipolarity, which is clearly seen especially for 3^+ excitations.

In the previous section we have mentioned that according to the TFFS all the irreducible axial-vector vertices in the nuclear matter should be renormalized. In our calculations such a renormalization was performed by multiplying all spin-isospin components of the t-matrix by the value of the quasiparticle local charge $e_q[\sigma\tau]$. In the case of anomalous parity excitations this corresponds to the multiplication of $d\sigma/d\Omega$ by the factor $e_q^2[\sigma\tau]$. For natural parity excitations renormalization is made only for the contribution of spin-flip components of transition densities. However, at energies $E_p \gtrsim$ 100 MeV in the direct processes the spin-flip transitions dominate in comparison with the non-spin-flip ones[15]. This is confirmed by the results shown in Table 1 where the spin-flip transitions obviously dominate (see also refs.[12,13]). Thus in constructing neutron spectra the factor e_q^2 is practically the fitting parameter whose value is chosen from the best fit of the low-energy part of the spectrum at small angles. For ^{90}Zr the value $e_q[\sigma\tau] = 0.8$ has earlier been found in ref.[13]. The preliminary results for ^{208}Pb given in that paper have been obtained with the same value of $e_q[\sigma\tau]$ but neglecting the contribution from most of the bound 1^+ and 3^+ states listed in Table 1, as well as 1^+ resonances above the GTR (19.2 MeV). As a result, in the low-energy part the integral cross sections were $\approx$ 15% smaller than the experimental ones. In the present paper this shortcoming was removed and the contribution of almost all transitions with $0 \leq L \leq 3$ was taken into account.

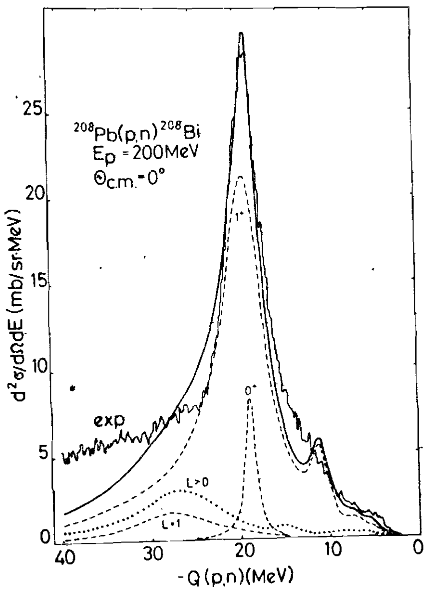

Fig. 1
Comparison of the calculated with $e_q[\sigma\tau] = 0.8$ energy spectrum for the reaction ^{208}Pb (p,n) ^{208}Bi at Ep=200 MeV and $\theta_{c.m.} = 0^{\circ}$ (solid line) with the experimental one [3] (broken line). The partial contributions from GT transitions (1^+), IAS (0^+), dipole transitions (L=1) and the summary background from multipole transitions ($L > 0$) are also shown.

The neutron spectra shown in figs. 1 and 2 as continuous distributions were obtained from the data of Table 1 by folding with the Breit-Wigner functions. The width parameter for discrete states was chosen equal to Γ = 1.2 MeV which approximately corresponds to the experimental energy resolution in ref.[3]. In the continuous spectrum region for the IAS Γ =1.4 MeV and for the other resonances the spreading width varied so as to reproduce the shape of the spectrum observed in the low-energy region $-Q \lesssim 25$ MeV. As a result, we used the values Γ = 2.0 MeV for the resonances with $\omega_R \leq 10$ MeV; 2.5 MeV in the region of $\omega_R \leq 15$ MeV; 5.5 MeV for the subsequent resonances up to $\omega_R \approx 21$ MeV and 8-10 MeV for the high-lying resonances. Thus some effects of multipair excitations were imitated that led to a natural width of resonances (see, e.g., the paper by Kuzmin and Soloviev[6]). The effects of tensor correlations (see, e.g., the paper by Bertsch and Hamamoto in ref.[6]) leading to transfer of the Gamow-Teller strength into the energy region $E_x \gtrsim \varepsilon_F$ as well as the effects of meson exchange currents and the coupling of GTR with excitations of the type of Δ -isobar-nucleon hole ($E_x \approx$ 300 MeV) are included into the local charge $e_q[\sigma\tau]$ in our approach.

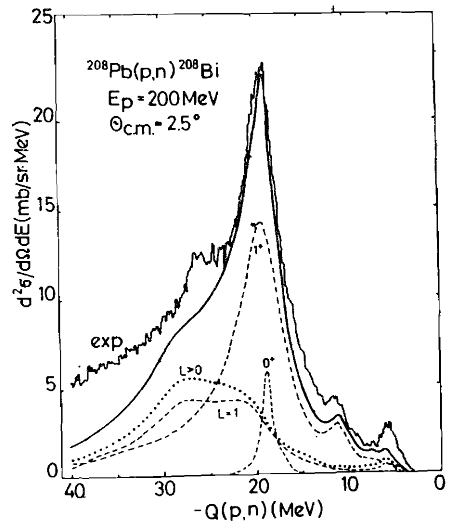

Fig. 2
The same as Fig. 1. but for $\theta_{c.m.} = 2{,}5^{\circ}$

The comparison of the results of calculations with the experimental spectra in figs. 1 and 2 gives for ^{208}Pb the value $e_q \approx 0.8$ as for ^{90}Zr. This implies that the integral strength of the low-energy splin-flip transitions with a small momentum transfer exhausts not more than 64% of the shell model sum rule (quenching effect). In fact, this is an upper limit value obtained under a natural condition of absence of any unknown background (e.g., connected with multi-step processes) in the low-energy region of experimental spectra.

Now we analyse the results shown in figs. 1 and 2, in particular, the partial contributions of different multipolarities. It is seen that the contribution of the Gamow-Teller transitions (1^+) dominates at small angles and the background under the GTR (the curve $L > 0$) is small. Quantitative integral estimates of contributions to the cross sections of different multipolarities and the experimental data for two regions of the neutron energy spectrum are presented in table 2. It turned out that the background of excitations with $L > 0$ under the GTR at $\theta = 0^\circ$ does not exceed 10% of the total cross section. However, the backround increases rapidly with θ, the main contribution coming from the spin-dipole transitions (L=1) that already at $\theta = 2.5^\circ$ form in the spectrum a well pronounced resonance in the region $20 \lesssim -Q \lesssim 30$ MeV.

Table 2. Integrated cross sections for the reaction ^{208}Pb (p,n) ^{208}Bi at E_p = 200 MeV. Experimental data taken from ref.[3] (estimated from spectra, for which we are grateful do Dr.C.Gaarde).

σ (mb/sr)	$0 \le -Q(p,n) \le 25$ MeV		$0 \le -Q(p,n) \le 40$ MeV	
	$\theta = 0^\circ$	$2{,}5^\circ$	0°	2.5°
$\sigma\ (0^+)$	17.0	12.0	17.7	12.5
$\sigma\ (1^+)$	164.3	107.0	206.7	136.9
σ (L=1)	7.2	34.2	21.3	71.9
σ (L>0)	17.8	42.3	44.3	91.4
σ_{total}	199.1	161,3	268.7	240.8
$\sigma_{exp.}$	$\approx$ 210	$\approx$ 185	$\approx$ 300	$\approx$ 300

The total integral cross sections, as is seen from Table 2, are in good agreement with experimental data in the region $-Q \lesssim 25$ MeV (having in mind a 5-10% accuracy of measurements) whereas higher in energy a deficit is gradually being accumulated. It is partially connected with the smoothing of the spectrum that leads to the transfer of the transition strength into the region $-Q > 40$ MeV (almost 10% of the total integral cross section). The compensation of this transfer could arise by taking account of the contributions from excitations in this energy region. Another reason is the attenuation of strength of the spin-flip transitions

(factor $e_q^2[\sigma\tau]$). However, we do not know the energy region where the missed strength is distributed. In particular, with inclusion of tensor correlations the mechanism of (2p-2h) admixtures may rather uniformly distribute a considerable part of the GT-strength far above the GTR[6]. This mechanism might enrich the high-energy part of the spectrum and it is thought to be most probable due to a large density of (2p-2h) excitations.

Conclusion

The present analysis has shown that a simple microscopic model of nuclear structure and the (p,n) reaction mechanism at intermediate proton energies provides a quantitative description of the neutron inclusive spectra at small angles in the excitation energy region including GTR ($0 \le -Q \lesssim 30$ MeV). At $\theta = 0^\circ$ in all the nuclei from ^{48}Ca to ^{208}Pb the background from multipole excitations is small, which enables one to obtain a quantitative estimate for the attenuation factor of the integral strength of spin-flip transitions ≈ 0.64. In the case of the Gamow-Teller transitions ($L=0,\ q \to 0$) this attenuation can be thought of as the renormalization of the constant of the weak axial-vector coupling $g_A \to e_q[\sigma\tau]\, g_A \equiv G_A \approx 1$. Analogous quantitative conclusions have recently been made while analysing β-transitions in some nuclear regions [20-23]. The constant of the π NN interaction is also renormalized in the matter $g_{\pi NN} \to e_q[\sigma\tau]\, g_{\pi NN} \equiv G_{\pi NN}$. The renormalization of both the constants is found to be important in evaluating of such effects as, e.g., the contribution of the pion mechanism to the EMC-effect[24-26].

It should be noted that the local charge of quasiparticles $e_q[\sigma\tau]$ enters into the M1 transition probabilities for 1^+ states and their excitation cross sections in the (p,p') reaction. It has been shown in refs.[27,28] that its inclusion leads to an agreement of calculations with the experimental data in ^{48}Ca, ^{90}Zr and ^{208}Pb.

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Исследование спектра нейтронов в реакции ^{208}Pb (p, n) ^{208}Bi при E_p = 200 МэВ

Представлены микроскопические расчеты спектра нейтронов в реакции ^{208}Pb (p, n) ^{208}Bi при E_p = 200 МэВ на малых углах. Показана применимость импульсного приближения метода искаженных волн и структурных представлений теории конечных ферми-систем для описания области низкоэнергетических возбуждений $0 \lesssim -Q \lesssim 30$ МэВ с малой передачей импульса. Получена количественная оценка величины локального заряда квазичастиц $e_q[\sigma\tau] \approx 0{,}8$, характеризующая ослабление интегральной силы спин-флиповых низкоэнергетических переходов, и обсуждаются связанные с ним эффекты.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

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Analysis of the Neutron Energy Spectra from the ^{208}Pb (p, n) ^{208}Bi Reaction at E_p = 200 MeV

Microscopic calculation of the forward-angle neutron energy spectra from the ^{208}Pb (p, n) ^{208}Bi reaction at E_p = 200 MeV are presented. It is shown that the distorted-wave impulse approximation (DWIA) and the microscopic theory of finite Fermi systems (TFFS) can be employed for describing the low-energy excitation region $0 \lesssim -Q \lesssim 30$ MeV with small momentum transferred. A quantitative estimate is obtained for the local charge of quasiparticles $e_q[\sigma\tau] = 0.8$ that characterizes the quenching of the integral strength of spin-flip low-energy transitions and the relevant effects are discussed.

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

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