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INVESTIGATION OF THE REACTION $^{16}O(p,n)^{16}F$ AT Ep=135 MeV

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1. Introduction

Charge-exchange reactions at intermediate energies have provided a considerable amount of new information on the isovector modes of excitation in nuclei [1]. Especially noticeable is the progress achieved recently in understanding the M1 and Gamow- Teller giant resonances (GT) with the (p,n) reaction [2,3]. The state excitation selectivity associated with the double spin - isospin transfer was discussed by G.E.Brown, J.Speth, and J.Wambach [4]. For references dealing with the description of properties of medium and heavy-weight nuclei in the spin-isospin channel we refer to the review articles [5-10]. The spin-isospin strength summed over all states was systematically found to exhaust approximately only 50 % [1] of the Ikeda sum rule strength[11] for medium and heavy-weight nuclei.

Recently B.D.Anderson et al.[12] have found that the total G T strength observed in the $^{18}O(p,n)^{18}F$ reaction at E_p = 135 MeV is about 67% of that expected from the Ikeda sum rule. This fraction is higher than that obtained in a similar analysis for medium- and heavy-weight nuclei, but is consistent with that measured for the $^{14}C(p,n)^{14}N$ reaction[13]. Transitions to the negative-parity states were observed in the $^{16}O(p,n)^{16}F$ reaction at E_p = 135 MeV[14]. The DWIA calculations have been compared with the measured angular distributions in a remarkable agreement. However, the normalizations required for the DWIA calculations performed with the nuclear wave-functions obtained from the shell-model predictions by Picklesimer and Walker[15] are between 0.23 and 0.47. The same normalization (0.34) was found for the GT transition in the $^{18}O(p,n)^{18}F$ reaction [12]. These normalizations are comparable to these required for (p,p')[16] and (e,e')[17] excitations of stretched states indicating that the normalization factors are necessary mainly to take account of unadequacy in the assumed nuclear wave functions and not in the reaction mechanism.

In the present work we analyse the transitions to the negative-parity states for the $^{16}O(p,n)^{16}F$ reaction at 135.2 MeV assuming that at these energies nuclear states are excited predominantly via one-step processes. We have used n-particle n-hole wave functions which have been tested extensively in different fields [18-20]. As a result, we have concluded that the normalization factors are now much closer to unity, they increase approximately twice as compared to calculations with $1p1h$ shell-model wave functions.

2. The Reaction Mechanism

Following ref.[21] we have assumed that for (p,n) reactions at intermediate incident energies the reaction mechanism consists of one-step direct transitions. Indeed, the explicit calculation of multistep reaction cross sections indicates that a single-step process should dominate at forward angles when the excitation energy is less than half the beam energy [22]. Double scattering becomes important only for fairly large energy transfer.The effective projectile-target-nucleon interaction can be approximated by a free N-N matrix. We have used a parametrization of Love and Franey[23] of the t - matrix by a sum of local Yukawa potentials. The parametrization is based on experimental phase-shift data for free N-N scattering.

We have developed our own version of the DWIA program based on Madsen's formalism[24]. A main advantage is that this formalism allows us to incorporate the n - particle n -hole nuclear wave functions. The program includes an exact treatment of knock-on exchange. Since those calculations were very time consuming, the computations reported in this paper were made by including the central and tensor terms of the effective interaction only. The microscopic spin-orbital interaction was not included in our program. However, its contribution is known to be very small for transitions to the negative-parity states[14]. We have used the optical model parameters determined by Comfort and Karp [25] for 135 MeV protons elastically scattered from ^{12}C .

3. Shell-Model Wave Functions of the A = 16 Nuclei

The simplest particle-hole- $(1p1h)$ - configuration-mixing model of the negative-parity excitations in A = 16 nuclei indeed describes only the gross features of photoabsorption, μ -capture and electron- and hadron-scattering reactions. In the present investigation we have used the n - particle n-hole $(n=0,1,2)$ model which has already manifested itself positively in the muon capture [18], radiative pion capture [19], and inelasitic neutrino-scattering [20] calculations. In the present section we shall describe this model.

In contrast to the early assumption of the closed p -shell $|0\rangle$ for the ground-state wave function of ^{16}O it very soon has become clear that the $2\hbar\omega$ and $4\hbar\omega$ admixtures have to be considered as well. An estimation by Brown and Green [26] shows for the ^{16}O ground state

$\|0\rangle$	$1p1h(2\hbar\omega)$	$2p2h(2\hbar\omega)$	$4p4h(4\hbar\omega)$
76%	≈ 0%	22%	<2%

In accordance with this result we have performed a diagonalization of a 44x44 Hamiltonian matrix constructed on the subspace of all $0\hbar\omega$ and $2\hbar\omega$ configurations. Details may be found in ref. [27]. We recall that five c.m. spurious states have in fact been projected out before diagonalization. To give a rough idea, we display here few most important terms

$$|^{16}O_{g.s.}\rangle = 0.888|0\rangle + 0.159|2p_{3/2}, 1p^{-1}_{3/2}\rangle + 0.169|(1d_{5/2})^2(1p_{1/2})^{-2}, 01\rangle -$$

$$-0.125|(1d_{5/2})^2(1p^{-1}_{3/2}, 1p^{-1}_{1/2}), 10\rangle + 0.146|(1d_{5/2}1d_{3/2})(1p^{-1}_{3/2}, 1p^{-1}_{1/2}), 10\rangle + \dots$$

For the negative-parity excitations one observes that there are a lot of configurations in the $3\hbar\omega$ band which should be admixed to the $1p1h$ ($1\hbar\omega$) states of the simple model. For instance, one finds about 1800 $3\hbar\omega$ configurations in the subspace $1^- T=1$. Here one clearly needs to introduce some further restriction on the basis. An analysis [28] of the electron and muon excitations of the giant dipole resonance has shown that the effect of $3p3h$ subspace is probably unimportant. In our calculation we have kept in the diagonalization those $2p2h$ ($3\hbar\omega$) configurations which are coupled most strongly (i.e., have a large nondiagonal matrix element) with the basic $1p1h$ components. In refs. [18-20] up to 95 of such components have been taken into account. The results are the following: (i) the amplitudes have been slightly diminished, namely, by ~ 2% for low-lying and by ~ 7% for high-lying negative-parity states, (ii) the relative contributions of the different $1p1h$ components were also slightly changed. The $J^- T=1$ nuclear states which carry the main spectroscopic strength are therefore basically of the $1p1h$ nature. The $3\hbar\omega$ admixtures are always smaller than 7 %. Centre-of-mass spurious contributions can stem in this case from the $3\hbar\omega$ sector only and are, in the present situation, unimportant.

The antisymmetrized DWIA transition amplitude for the nucleon-nucleus scattering can be written as [29]

$$T_{fi} = \int d\vec{r}_0\, \chi_f^{(-)*}(\vec{r}_0, \vec{k}_f) \langle B\beta | \sum_i t(0,i)(1-P_{0i}) | A\alpha\rangle \chi^{(+)}(\vec{r}_0, \vec{k}_i), \quad (1)$$

where $\chi^{(\pm)}$ are distorted waves, $|\alpha\rangle$ and $|\beta\rangle$ are the projectile spin-isospin wave functions, $|A\rangle$ and $|B\rangle$ are initial and final nuclear states, the operator $t(0,i)$ allows for the interaction of a projectile particle 0 with a nucleus particle i . The second term in the (1) is responsible for the exchange in the nucleon- nucleus scattering and can be treated in terms of the DWIA including a nonlocal form factors [24] and nonlocal nuclear transition densities:

$$\rho^{\ell s j, T}_{\ell_1 \ell_2}(r_0, r_0') = \langle J_B T_B \| \sum_i \frac{\delta(r_0 - r_i')\delta(r_i - r_0')}{r_i^2 r_i'^2} T^{\ell s j}_{\ell_1 \ell_2}(i,i') \tau^T(i) \| J_A T_A \rangle =$$
$$= \sum_{n_1 j_1 n_2 j_2} 2\hat{T}\hat{S}\hat{\ell}\hat{j}\hat{j}_1\hat{j}_2 (-1)^{\ell-\ell_2} \begin{Bmatrix} \ell & s & j \\ \ell_2 & 1/2 & j_2 \\ \ell_1 & 1/2 & j_1 \end{Bmatrix} R_{n_1\ell_1 j_1}(r_0') R_{n_2 \ell_2 j_2}(r_0) S(J_A J_B, j_1 j_2) \delta_{j J_B} \delta_{T T_B}, \quad (2)$$

where $R_{n\ell j}(r)$ are radial single-particle wave functions and $S(J_A J_B, j_1 j_2)$ is the spectroscopic amplitude [24]. Correspondingly, the local nuclear transition densities entering into the direct transition amplitudes can be written as:

$$\rho^{\ell s j, T}(r_0) = \langle J_B T_B \| \sum_i \frac{\delta(r_0 - r_i)}{r_i^2} T^{\ell s j}(i) \tau^T(i) \| J_A T_A \rangle =$$
$$= \sum_{n_1 j_1 \ell_1 n_2 j_2 \ell_2} \frac{2\hat{T}\hat{S}\hat{\ell}\hat{j}\hat{j}_1\hat{j}_2\hat{\ell}_1}{\sqrt{4\pi}} \begin{Bmatrix} \ell & s & j \\ \ell_2 & 1/2 & j_2 \\ \ell_1 & 1/2 & j_1 \end{Bmatrix} (\ell_1 0 \ell 0 | \ell_2 0) R_{n_1 \ell_1 j_1}(r_0) R_{n_2 \ell_2 j_2}(r_0) \ast$$
$$\ast S(J_A J_B, j_1 j_2) \delta_{j J_B} \delta_{T T_B}, \quad (3)$$

where

$$T^{\ell s j m}_{\ell_1 \ell_2}(i,i') = \sum_{m_\ell m_s} (\ell m_\ell s m_s | j m) \mathcal{Y}^{\ell m_\ell}_{\ell_1 \ell_2}(\hat{r}_i, \hat{r}_i') \sigma^s_{m_s}(i), \quad (4)$$

$$\mathcal{Y}^{\ell m_\ell}_{\ell_1 \ell_2}(\hat{r}_i, \hat{r}_i') = \sum_{m_1 m_2} (\ell_1 m_1 \ell_2 m_2 | \ell m_\ell) Y_{\ell_1 m_1}(\hat{r}_i) Y_{\ell_2 m_2}(\hat{r}_i').$$

If one uses the harmonic-oscillator wave functions to represent the transition densities it is convenient to write:

$$\rho^{\ell s j, T}_{\ell_1 \ell_2}(r_0, r_0') = (r_0/R)^{d_2} (r_0'/R)^{d_1} (A + B(r_0'/R)^2 + C(r_0/R)^2 + D(r_0 r_0'/R^2)^2) \ast \quad (5)$$
$$\ast \exp\{-((r_0/R)^2 + (r_0'/R)^2)/2\}$$

$$\rho^{\ell s j, T}(r_0) = (r_0/R)(C1 + C2(r_0/R)^2 + (r_0/R)^4) \exp\{-(r_0/R)^2\}, \quad (6)$$

where R is the oscillator radius, d_i equals $1(0)$, if ℓ_i is odd (even). The coefficient $A, B, C, D, C1, C2$ and $C3$ for the transition considered in this paper are presented in Tables 1 and 2; the oscillator radius R is equal to 1.67 fm for these states.

4. Discussion of Results

The DWIA calculations for the negative-parity states are compared in Figs. 1-5 with the measured angular distributions at 135.2 MeV /14/. The normalization factors $N = \sigma^{exp}/\sigma^{theor}$ required to make the DWIA calculations to agree in magnitude with the observed cross sections are given in Table 3.

In the usual $1p1h$ shell-model the 4^- state contains a stretched configuration $(\pi d_{5/2}, \nu p_{3/2}^{-1})$ and the transition to the 4^- state is dominated by the isovector tensor term in the effective N-N interaction.

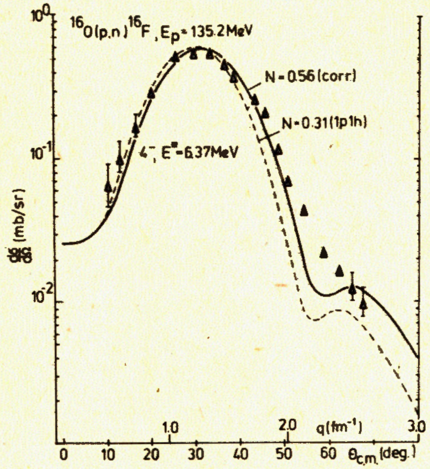


Fig. 1.

Comparison of the measured angular distribution /14/ at 135 MeV for transition to the 4^-(E^* = 6.37 MeV) state in the reaction $^{16}O(p,n)^{16}F$. The DWIA calculation is based on effective N-N interaction of Love and Franey /23/ and the optical model parameters of Comfort and Karp /25/. The dashed curve is calculated with the stretched particle-hole $(\pi d_{5/2}, \nu p_{3/2}^{-1})$ configuration and the full line with the correlated wave functions /18-20/. The normalization factors N are shown in figure.

The calculated cross sections (Fig. 1) agree well with the measured angular distributions, but the normalization factor equals 0.31 as has been found in /14/. Almost the same normalization (0.44, Ref. /17/) is required for the (e , e') excitation of this state. If the multiparticle-multihole configurations are included in the shell -model description of the initial and final states, the N factor is enhanced about twice relative to the $1p1h$ case and becomes equal to 0.56. Note that the angular distributions are not sensitive at small angles to multiparticle-multihole configurations. Very similar results for the excitation of 4^- level have been obtained in ref. /30/.

As is seen from Figs. 2 and 3, the calculated cross sections for two 2^- states with the excitation energies 0.4 and 7.6 MeV are fitted well except the angular distribution for the state 0.4 MeV which has a shoulder near 35°, and the theoretical cross sections is underestimated in this angular region. The normalization factor N increases from 0.47 (0.24) up to 0.78 (0.42) for the state with E^* = 0.4 MeV (7.6 MeV) due to the correlations included in the wave functions. The shoulder near 35° for the state at 0.4 MeV can be explained, if one assumes /14/ that this transition is an unresolved transition consisting of two states: one of them is the 2^- state at 0.4 MeV and the second is the 3^- state at 0.7 MeV.

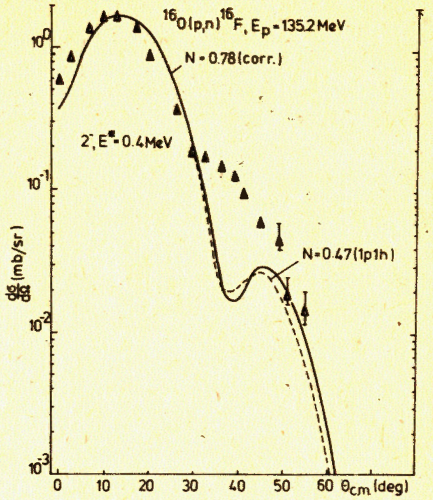


Fig. 2.

The differential cross sections for transitions to the unresolved states at E^* = 0.4 and 0.7 MeV compared with DWIA calculations for the 2^- state. The dashed curve is calculated with the $1p1h$ shell-model wave functions /15/ and the full line with the correlated ones /18-20/.

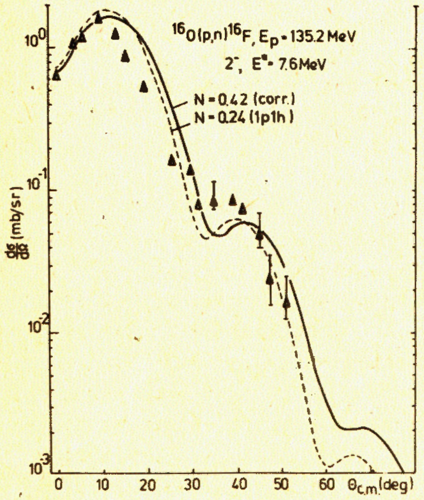


Fig. 3.

Comparison of the measured angular distribution /14/ for transition to the state at E^* = 7.6 MeV with DWIA calculations for the 2^- state.

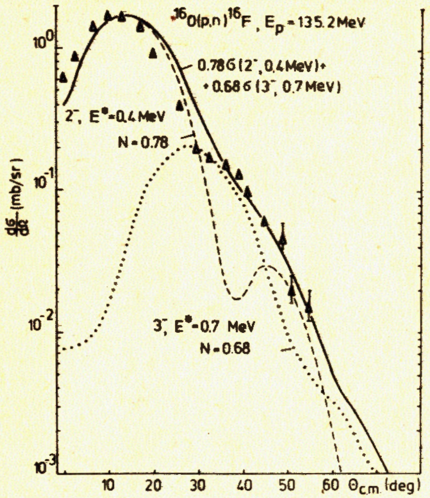


Fig. 4.

Comparison of the experimental angular distribution /14/ for transitions to the unresolved states at E^* = 0.4 and 0.7 MeV with DWIA calculations for the 2^- (dashed curve) and 3^- (dotted curve). All calculations have been made with the correlated wave functions. The full line is the sum

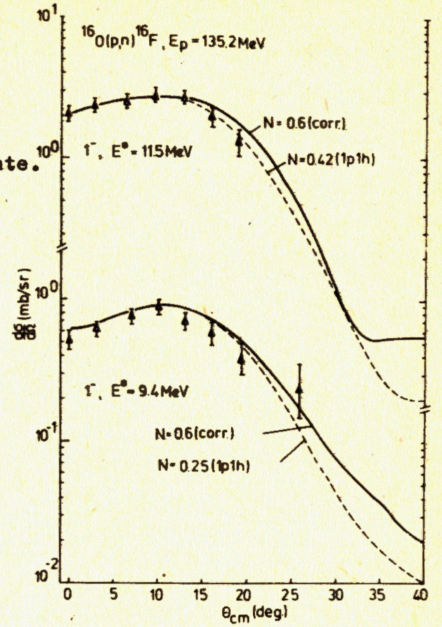
$$\frac{d\sigma}{d\Omega} = 0.78\frac{d\sigma}{d\Omega}(2^-, 0.4\,MeV) + +0.68\frac{d\sigma}{d\Omega}(3^-, 0.7\,MeV).$$

The normalization factor N for this last state is 0.23 (0.68) without (with) the correlations in the used transition densities. Comparison of the measured angular distribution at 135 MeV for the transitions to the unresolved states at E^* = 0.4 MeV and 0.70 MeV with DWIA calculations for the 2^- state and 3^- state are given in Fig. 4. The full curve represents the calculated cross section $\frac{d\sigma}{d\Omega}$ = 0.78 $\frac{d\sigma}{d\Omega}$ (2^-, 0.4 MeV) + 0.68 $\frac{d\sigma}{d\Omega}$ (3^-, 0.7 MeV) with the correlated wave functions. The excitations of both, 2^- state and 3^- state have included approximately equal contributions from the isovector tensor and central term, as is noted in /14/. The 2^- (7.6 MeV) level in ^{16}N has its isobar analogue in ^{16}O at E^* = 20.4 MeV observed /31/ with $B(M2)$ = 467 ± 156 $\mu_0^2 \cdot fm^2$. Besides that the (e, e') experiment /31,32/ reveals in ^{16}O a strong ($B(M2)$ = 338 ± 68 $\mu_0^2 \cdot fm^2$) excitation at E^* = 19.0 MeV. It has been suggested by Speth et al. /33/ that the shell-model 2^- state calculated at E^* = 19.5 MeV corresponds to the sum of two levels. Such an interpretation is also supported /19/ by the ^{16}O (π^-, γ) data. One expects a similar situation in the ^{16}O (n, p) ^{16}N reaction as well. Would such structure be observed it can provide an explanation of the irregularly low value (0.42) of the normalization coefficient (see table 3) obtained when the 2^- (7.6 MeV) level alone is compared with the shell structure

$$\sim 0.6|p_{3/2}^{-1}, s_{1/2}\rangle \quad + 0.75|p_{3/2}^{-1}, d_{5/2}\rangle$$

Fig. 5.

Comparison of the experimental data /14/ for transitions to the states at 9.4 and 11.5 MeV with DWIA calculations for the 1^- state.



In Fig.5 we compare the experimental angular distributions with our calculations for the two 1^- states at E^* = 9.4 and 11.5 MeV. Again, the effect of multiparticle-multihole configurations of the investigated states has increased the normalization factor from 0.25 (0.42) up to 0.6 (0.6) for the 1^- state at E^* = 9.4 (11.5) MeV. These excitations are dominated by the isovector central component of the N-N force.

In Fig.6 we give the transition densities $\rho^{\ell s j, T}(r)$ for 1^- (E^* = 9.4 MeV) state in coordinate space, and in Fig.7 - in the momentum space $(\rho^{\ell s j, T}(q) = \int j_\ell(qr)\rho^{\ell s j, T}(r)r^2 dr)$. Dashed and dot-dashed curves is transition density in the $1p1h$ shell-model basis, the full line takes into account the correlations. The calculations with manyparticle-manyhole configurations diminishes transition densities on the nuclear surface and enriches them inside the nucleus. Accordingly, in the momentum space transition densities with correlations are decreased at low and increased at larger momentum transfers. As a consequence we observe modifications in theoretical cross sections discussed above.

The calculated and measured angular distributions are generally in good agreement for all the analysed negative-parity states verifying that (p,n) reactions at intermediate energies proceed mainly via one-step direct transitions. The utilization of correlated wave functions has diminished the absolute value of the cross sections about twice, exceeding nevertheless the experimental one 1.3 to 2.3 times. It is possible to bring several reasons for explaining this deficiency. That can be contribution of the $npnh$ component of nuclear states, omitted in the calculations, the medium and other corrections to the NN interactions, uncertainties of the optical parameters, and so on.

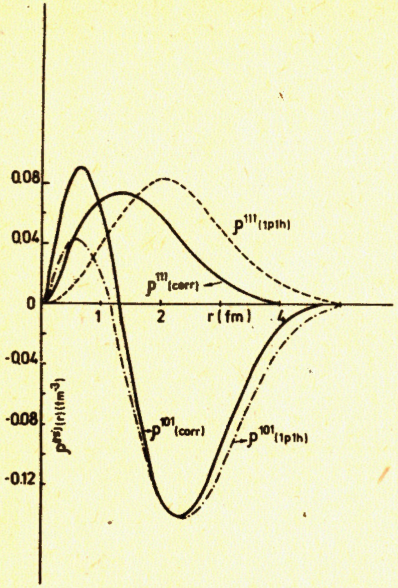


Fig. 6.

Transition density for 1^- $E^* = 9.4$ MeV state in coordinate space. Dashed and dot-dashed curves is calculation in *1p1h* basis, the full line is calculation with correlations.

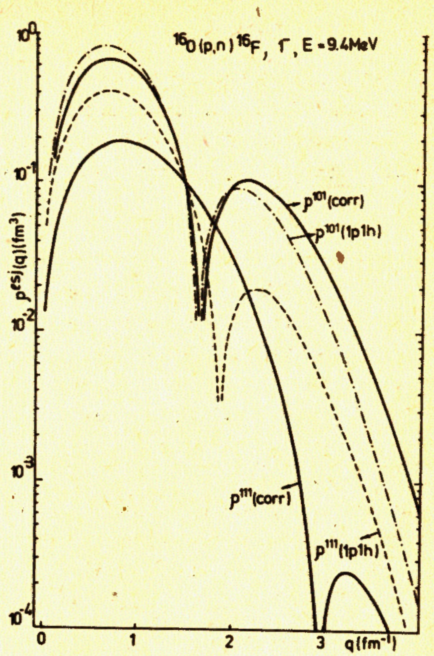


Fig.7.

Transition density for 1^- $E^* = 9.4$ MeV state in momentum space. The meaning of curves is the same as in fig.6.

5. Conclusion

The present work demonstrates that prospects for a quantitative microscopic understanding of intermediate-energy charge-exchange reactions are promising. We have shown that the results are sensitive to the choice of nuclear densities. The realistic wave functions tested in different fields provide a satisfactory description of spin-isospin excitations. It is possible that the remaining deficiencies are due to inaccuracies in the two-nucleon effective interaction which can entail medium corrections. These corrections as has been shown /34,35/ play an important role in the isoscalar spin-independent central component of the N-N effective interaction.

Table 1

Parameters of the local transition densities (6) calculated from the correlated wave functions described in text

J^π	E^*(Mev)	(l,s,j)	c_1	c_2	c_3
2^-	0.4	(1,1,2)	0.02414	-0.27984	-0.00004
		(3,1,2)	0.0	0.06735	-0.00099
3^-	0.7	(3,1,3)	0.0	0.27518	-0.00072
		(3,0,3)	0.0	-0.23067	0.00008
4^-	6.37	(3,1,4)	0.0	-0.67106	0.03020
2^-	7.6	(1,1,2)	-0.58400	0.74533	-0.03142
		(3,1,2)	0.0	0.14779	-0.00508
1^-	9.4	(1,1,1)	0.15049	0.03899	-0.00271
		(1,0,1)	0.35781	-0.59996	0.02393
1^-	11.5	(1,1,1)	-0.059267	0.41442	-0.01828
		(1,0,1)	-0.06957	0.16633	-0.00556

Table 2

Parameters of the nonlocal transition densities (5) calculated from the correlated wave functions described in text

J^π	E^*(Mev)	(l,s,j)	(l_1,l_2)	A	B	C	D
2^-	0.4	(1,1,2)	(1,2)	0.0	0.0	0.73459	0.00181
			(2,1)	0.0	-0.07772	0.0	0.0
			(1,0)	0.07772	-0.00361	-0.05366	0.00240
			(0,1)	0.00784	-0.00522	0.0	0.0
		(3,1,2)	(1,2)	0.0	0.0	0.23205	-0.00309
			(2,1)	0.0	-0.02150	0.0	0.0

Table 2 (continued)

J^{π}	E^*(Mev)	(ℓ,s,j)	(ℓ_1,ℓ_2)	A	B	C	D
3^-	0.7	(3,1,3)	(1,2)	0.0	0.0	0.90087	-0.00227
			(2,1)	0.0	-0.04056	0.0	0.0
		(3,0,3)	(1,2)	0.0	0.0	-0.74201	0.00025
			(2,1)	0.0	0.02087	0.0	0.0
4^-	6.37	(3,1,4)	(1,2)	0.0	0.0	-2.10804	0.09442
			(2,1)	0.0	0.01009	0.0	0.0
2^-	7.6	(1,1,2)	(1,2)	0.0	0.0	-0.85289	0.03258
			(2,1)	0.0	0.06535	0.0	0.0
			(1,0)	-2.11234	0.09799	1.45845	-0.06533
			(0,1)	0.04210	-0.02806	0.0	0.0
		(3,1,2)	(1,2)	0.0	0.0	0.46744	-0.01588
			(2,1)	0.0	-0.00539	0.0	0.0
1^-	9.4	(1,1,1)	(1,2)	0.0	0.0	-0.41704	0.00230
			(2,1)	0.0	0.03486	0.0	0.0
			(1,0)	0.54082	-0.03441	-0.37278	0.02294
			(0,1)	-0.00735	0.00490	0.0	0.0
		(1,0,1)	(1,2)	0.0	0.0	0.91347	-0.03478
			(2,1)	0.0	-0.06738	0.0	0.0
			(1,0)	1.29417	-0.05344	-0.89399	0.03563
			(0.1)	-0.02576	0.01717	0.0	0.0
1^-	11.5	(1,1,1)	(1,2)	0.0	0.0	-1.02190	0.04165
			(2,1)	0.0	0.09228	0.0	0.0
			(1,0)	-0.22749	0.00883	0.15718	-0.00589
			(0,1)	0.01739	-0.01159	0.0	0.0
		(1,0,1)	(1,2)	0.0	0.0	-0.31017	0.00806
			(2,1)	0.0	0.02235	0.0	0.0
			(1,0)	-0.24304	0.01249	0.16772	-0.00833
			(0,1)	-0.00356	0.00238	0.0	0.0

Table 3

The normalization factors $N=\sigma^{exp}/\sigma^{theor}$

J^{π}	E^* (MeV)	N(1p1h)	N(npnh)
2^-	0.4	0.47	0.78
3^-	0.7	0.23	0.68
4^-	6.37	0.31	0.56
2^-	7.6	0.24	0.42
1^-	9.4	0.25	0.60
1^-	11.5	0.42	0.60

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Исследование реакции $^{16}O(p,n)^{16}F$ при E_p = 135 МэВ

Проведен анализ реакции $^{16}O(p,n)^{16}F$ в рамках импульсного приближения метода искаженных волн (DWIA). В расчетах учитывался вклад как прямого, так и обменного выбивания нуклонов. Включение n-частичных n-дырочных (n = 0, 1, 2) корреляций в волновые функции ядер A = 16 улучшает описание экспериментальных данных: абсолютные значения сечений уменьшаются в среднем в два раза по сравнению с расчетами, использующими простые частично-дырочные модели структуры ядра.

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Investigation of the Reaction $^{16}O(p,n)^{16}F$ at E_p = 135 MeV

The $^{16}O(p,n)^{16}F$ reaction at 135 MeV has been analyzed within the distorted-wave impulse-approximation (DWIA). Both direct and knock-out exchange amplitudes are taken into account. Including the n-particle n-hole (n = 0, 1, 2) correlations in the wave functions of A = 16 nuclei improves the description of experimental data: diminishes the absolute value of the cross sections about twice as compared with the calculations using the simple particle-hole structure models.

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

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