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INVESTIGATION OF THE $0^+ - 0^-$ TRANSITIONS IN $^{16}O(p, p')^{16}O$ AND $^{16}O(p, n)^{16}F$ REACTIONS AT $35 \leq E_p \leq 135$ MeV

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INTRODUCTION

At present, the studies of nucleon quasielastic scattering (inelastic scattering, charge-exchange reactions, etc.) produce extensive information on the properties of excited atomic nuclei. At energies of incident nucleons from several dozen to several hundred MeV experimental data are analysed by a microscopic version of the distorted-wave method (DWIA). Microscopic calculations within DWIA require the knowledge of the nuclear transition density, effective interaction between an incident nucleon and nucleons in a nucleus, and of optical potentials. In practice, such calculations involve a large amount of parameters, and to make the experimental information more reliable, one should fix parameters from independent sources, and examine the sensitivity of results to their alternations. The study of excitation of nuclear transitions with a certain selectivity puts limits on the number of varied parameters and thus simplifies the analysis of reactions. Among such excitations $0^+ \to 0^-$ transitions possess a peculiar selectivity: they may be excited only by longitudinal external fields $(\bar{\sigma} \cdot \bar{r})$ and are most sensitive to the tensor correlations. Spin-orbital components of the effective interaction do not contribute to the cross section, which allows us to study the properties of central and tensor components.

Excitation of charge-exchange 0^- resonances in a wide mass region of nuclei was studied in reactions with charged pions[1]. There are evidences of their presence in (p,n) reactions at intermediate energies[2]. In the neutral channel, apart from the excitation of two 0^- states in (p,p') reaction on ^{16}O, 0^--resonances are not yet found (the possibility of observation of the 0^--states in scattering of protons with an intermediate energy on medium and heavy nuclei has been discussed in[3]). The most studied are $0^+ \to 0^-$ transitions in light systems with A = 16. Kelly[4] observed the isoscalar $0^+ \to 0^-$ transition in inelastic scattering $^{16}O(p,p')^{16}O$ at the proton energy 135 MeV, Hosono et al.[5] founs isoscalar and isovector transitions in the same reaction at energy 65 MeV and Ohnuma et al.[6] fixed them at energy 35 MeV. Isovector transitions in the charge-exchange reaction $^{16}O(p,n)^{16}F$ at proton energies 35 MeV and 80 MeV were investigated in[7,8].

In this paper, we calculated differential cross sections and analysing powers for the excitation of isoscalar and isovector 0^- states in quasielastic scattering of protons on ^{16}O and compared the calculated results with the available experimental data. Also, we studied the sensitivity of calculations to different versions of the effective internucleon interaction, optical potentials, and transition densities. It has been shown that in general we correctly understand the mechanisms of excitation of 0^- states except for the charge-exchange reaction at E_p = 35 MeV where we cannot describe the experimental data at transfer momenta from 1.5 fm^{-1} to 2.0 fm^{-1}. This work is a further extension of ref./9/ devoted to the study of $0^+ \to 0^-$ transitions in quasielastic reactions $p + {}^{16}O$.

2. REACTION MECHANISM

We assume the mechanism of (p,p′) and (p,n) reactions at studied energies of projectiles to be direct and single-step. In/9/ we have substantiated this assumption. Therefore, the excitation of $0^+ \to 0^-$ transitions was calculated within DWIA with explicit consideration of exchange effects/10/.

An important element specifying the process dynamics is the effective interaction of an incident nucleon with nucleons of the target-nucleus. During the last ten years an essential progress was achieved in the understanding of effective interactions, a starting point for their construction being realistic NN-potentials (at intermediate energies, experimental amplitudes of free NN scattering). The present calculations at energies of several dozen MeV per nucleon were based on M3Y/11/ and ATB/12/ forces. The M3Y forces were obtained on the basis of Hamada-Johnson and Reid potentials, whereas the ATB forces on the basis of the Paris potential.

At energies of an incident nucleon of an order of 100 MeV and higher the use was made of LF forces/13/ and their modified version LF (1985)/14/ derived from the NN-amplitude within the impulse approximation. The LF forces depend, while the M3Y and ATB do not depend on the energy of an incident nucleon. Besides, in calculations we employed the forces vG dependent on energy and density/15/ obtained from the Paris potential by solving the Bethe-Goldstone equation in the local-density approximation.

Parameters of the optical potential (see Table 1) were taken from/16/ at E_p = 35 MeV, from/17/ at E_p = 65 MeV, and from/18,4/ at E_p = 80 MeV and E_p = 135 MeV. For energies 35; 65 and 80 MeV optical potentials were taken different in the initial and final channel, the Q-value of the reaction being taken into account, and for E_p = 135 MeV they were chosen the same in both the channels, three different variants being considered, describing the experimental data on elastic scattering.

Table 1

Parameters of the optical potential which have been used in calculations

E_p MeV	r_c fm	V MeV	r_v fm	a_v fm	W MeV	r_w fm	a_w fm	W' MeV	$r_{w'}$ fm	$a_{w'}$ fm	V_{LS} MeV fm^2	W_{LS} MeV·fm^2	r_{LS} fm	a_{LS} fm
35 /16/ (in)	1.20	-47.893	1.1099	.6764	-3.700	1.252	.678	11.843	1.252	.678	-22.400	0.0	1.010	.600
/16/ (*out*)	1.20	-51.100	1.1700	.7500	-1.439	1.320	.422	34.410	1.320	.422	-24.800	0.0	1.000	.700
65/17/ (in)	1.25	-27.172	1.297	.6556	-12.847	0.2762	1.198	13.160	1.350	.375	-23.172	0.0	1.057	.5807
50/17/ (*out*)	1.25	-39.620	1.160	.7500	- 5.925	1.370	0.320	6.300	1.370	.320	-12.080	0.0	1.064	.780
80 /18/ (in)	1.30	-27.000	1.200	.630	- 8.300	1.375	.663	0.0	-	-	-23.000	0.0	.900	.500
63 /18/ (*out*)	1.30	-32.400	1.200	.6215	- 7.500	1.400	.675	0.0	-	-	-22.500	0.0	.900	.500
135/18/ (CK)	1.25	-16.200	1.200	.660	-11.100	1.280	.630	0.0	-	-	-17.800	0.0	.900	.500
135/4/ (KA)	1.20	-18.460	1.210	.770	- 6.660	1.510	.420	0.0	-	-	-14.680	1.360	1.004	.487
135/4/ (KB)	1.20	-15.300	1.350	.630	-11.260	1.330	.590	0.0	-	-	-15.600	1.000	.960	.490

where $U(r) = V_{coul}(r) + Vf(x_v) + iWf(x_w) + iW'a_{w'}\frac{d}{dr}f(x_{w'}) + \frac{1}{r}(V_{LS} + iW_{LS})\frac{d}{dr}f(x_{LS})(\vec{L}\cdot\vec{S})$

$x_a = (r - R_a)/a_a, \quad R_a = r_a A^{1/3}, \quad f(x_a) = [1 + \exp\{-x_a\}]^{-1}.$

In calculations, the structure of $0^+ \to 0^-$ transitions was considered either as an excitation of a simple particle-hole configuration $(2s_{1/2}, 1p^{-1}_{1/2})$, or in the (np,nh) (n = 0,1,2) model a more detailed discussion of which may be found in [9,10].

3. CALCULATED RESULTS AND DISCUSSION

In Figs.1,2 and 3 we compare the results of theoretical calculations of differential cross sections and analysing powers with experimental data. Normalization factors $N = \sigma_{exp}/\sigma_{theor}$ necessary to bring into an agreement the calculated and experimental cross sections are presented in Tables 2 and 3.

The discussion of results corresponding to the use of a correlated (np,nh) wave function as compared with calculations for a pure configuration was already carried out in ref. [9]. Here we only notice the increase of the normalization factor when (np,nh) wave functions are used. The ratio $N(2s_{1/2}, 1p^{-1}_{1/2})/N(np,nh)$ in the case of M3Y forces equals 0.6÷P 0.65 for isovector transitions and ~1.0 for isoscalar (E_p = 65 MeV) transition, whereas for LF (1981) and isoscalar transition it amounts to 0.75÷0.80. In Fig.3 we compare theoretical calculations with new experimental data [6] on the excitation of isovector and isoscalar 0^- states in inelastic scattering of 35 MeV protons. Theoretical angular distributions reproduce, in general, the behaviour of experimental cross sections though there are differences in details. The calculations also provide a qualitative description of the behaviour of the analysing power for isoscalar transition, while for the isovector transition data are worse reproduced. Note that the 0^-, T = 1 state with excitation energy 12.795 MeV is an analogue to the ground 0^- state in ^{16}F. Therefore, if the excitation mechanism of analogue states in (p,p′) and (p,n) reactions is the same (direct single-step process) and isotopic invariance is preserved, the cross section of excitation of an analogue state in (p,n) reaction is twice that of the corresponding state in (p,p′) reaction. Comparison [20] of the excitation cross sections of analogue states (4^-, T = 1, E* = 6.37 MeV in ^{16}F and 4^-, T = 1, E* = 18.98 MeV in ^{16}O) in the course of scattering of 135 MeV protons on ^{16}O supports the above conclusion. Experimental cross sections are in excellent agreement with each other both in shape and absolute value (upon multiplying the experimental cross sections of (p,p′) reaction by factor of two). At proton energy 35 MeV a different experimental pattern is observed. The cross section of excitation of an analogue state in inelastic scattering is twice as much as that in (p,n) reaction. Several sources are possible for the above disagreement: experimental uncertainties (background subtraction) in the separation of the

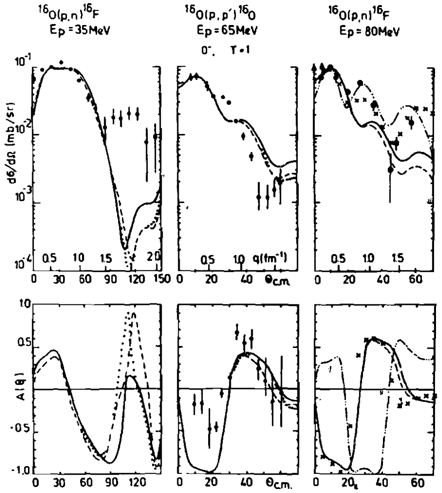

Fig.1. The differential cross sections for $^{16}O(p,n)^{16}F$ *(0^-, T = 1, ground state) at proton energies 35 and 80 MeV and* $^{16}O(p,p')^{16}O$ *(0^-, T = 1, E* = 12.795 MeV) at* E_p *= 65 MeV, and analysing powers* A(θ). *Calculations with the simple particle-hole* $(2s_{1/2}, 1p^{-1}_{1/2})$ *configuration (- - - M3Y), and with the* (np,nh) *wave functions (——M3Y, ······· - ATB, ——··——LF (1981),* *** *- vG).*

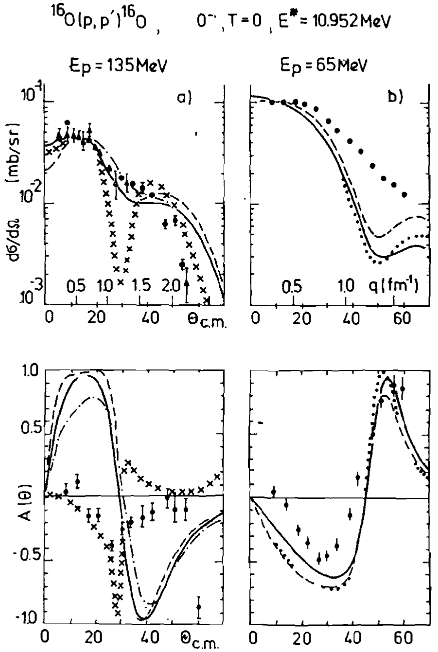

Fig.2. The differential cross sections for $^{16}O(p,p')^{16}O$ *(0^-, T = 0, E* = 10.952 MeV) and corresponding analysing powers. a)* E_p *= 135 MeV. The simple single-particle* $(2s_{1/2}, 1p^{-1}_{1/2})$ *configuration (- - - LF (1981)) and the correlated* (np,nh) *wave function (——LF (1981), ——·——LF (1985),* **** *- vG). b)* E_p *= 65 MeV. The simple configuration (- - - M3Y) and the correlated wave functions (—— M3Y, ···· - ATB).*

0^--excitations, violation of the isotopic invariance, or, which is most likely, different excitation mechanisms, i.e., possible contributions of mulistep processes. For (p,n) reaction at E_p = 35 MeV we could not have calculated the experimentally observed rise of the cross section in the range of transferred momenta 1.5 fm$^{-1} \lesssim q \lesssim 2.0$ fm^{-1} In ref. [21] an attempt was undertaken to relate the above discrepancy with the influence of the pion field in nuclei. At the same time, in (p,n) reaction at E_p = 80 MeV no discrepancy arose between theoretical calculations and experimental data (Fig.1, calculations with forces LF(100) and vG(100)). This leads us to the assumption that during the excitation of 0^- states in scattering of E_p = 35 MeV protons multistep processes may be important since, as a rule[22], with increasing energy of the projectiles the contribution of multistep processes to the cross section rapidly decreases.

Table 2

Normalization factors $N = N_{exp}/N_{theor}$

Reaction	(MeV)	M3Y	ATB	LF (1981)	LF (1985)	vG
(p, n)	35	.42 (.27)	.52	–	–	–
	80	.17 (.10)	.19	1.00	.90	.62
(p, p´)	35	1.0(1.0)*	–	–	–	–
		1.15 (0.70)	–	–	–	–
	65	.45 (.48)*	.50*	–	–	–
		.24 (.15)	.27	–	–	–
	135	–	–	.66*	.65*	.45*

* The symbol * refers to the isoscalar transition.

Table 3

Normalization factors $N = N_{exp}/N_{theor}$ for the isoscalar transition $0^+ \rightarrow 0^-$ at E_p = 135 MeV and different optical potentials

	LF (1981)	LF (1981)	LF (1985)	vG
CK[18]	(.49)	.66	.65	.45
KA[4]	(.40)	.50	.45	.40
KB[4]	(.52)	.70	.69	.48

A simple particle-hole configuration $(2s_{1/2}, 1p^{-1}_{1/2})$ is marked by brackets in Tables 2 and 3.

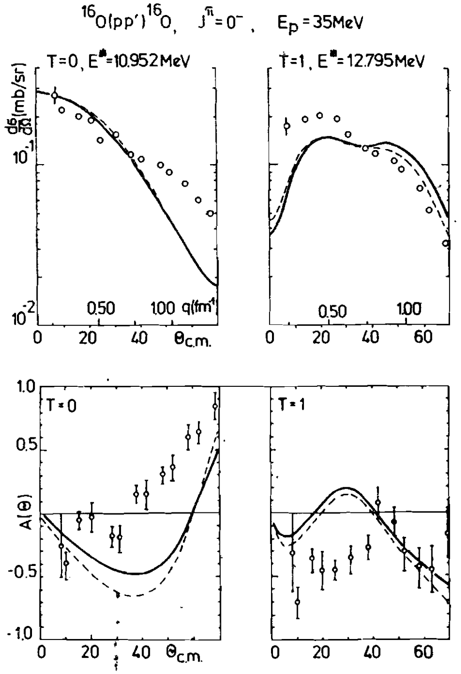

Fig.3. The differential cross sections for reaction $^{16}O(p,p')^{16}O$ *with excitation of isoscalar* (E* = 10.952 MeV) *and isovector* (E* = 12.795 MeV) 0^-*-states and corresponding analysing powers. The meaning of curves is the same as in Fig.1.*

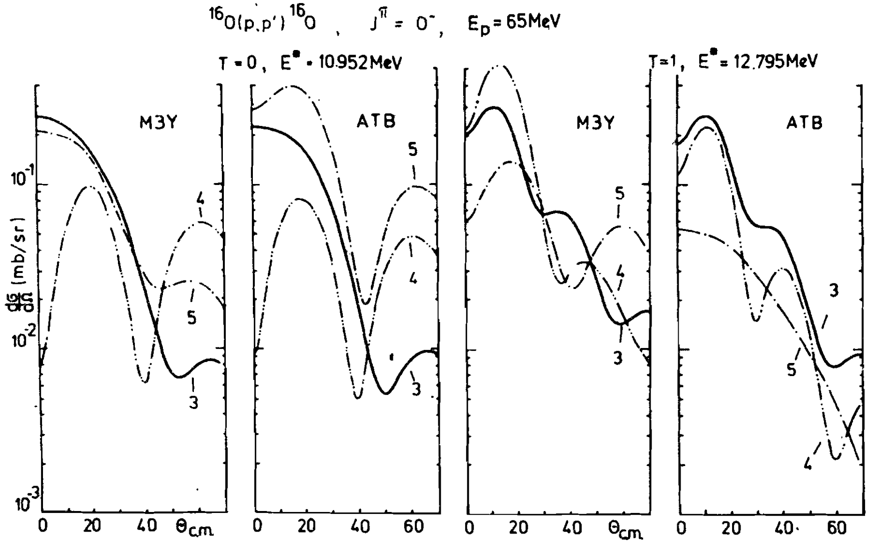

Fig.4. The differential cross sections for the reaction $^{16}O(p,p')^{16}O$ *with the* (np, nh) *wave functions and forces M3Y and ATB. 3.* ——— (D + Kn), *4.* ———..——— D, *5.*—.— Kn, *where* D – *direct component and* Kn – *knock-on component.*

Next, we note insignificant differences in the cross sections and analysing powers (see Figs. 1 and 2) calculated with forces M3Y and ATB, while the direct and exchange parts of cross sections calculated separately (Fig.4) essentially differ from each other. From comparison of M3Y and ATB forces /19/ it follows that even singlet (SE) and triplet (TE) components of these forces are close to each other, and odd ones (singlet and triplet, SO and TO) significantly differ from each other. The exchange amplitude is determined by effective forces obtained from interaction in the direct channel by changing signs of odd components. In the approximation of zero-range interaction (δ-force) for odd components the exchange amplitude coincides with the direct one in magnitude and is opposite in sign so that they cancel out in the total amplitude. This shows the uncertainty in odd components of effective forces due to adding either a δ-function in the coordinate space or a constant in the momentum space. Upon renormalization /19/ (introduction of a constant in the momentum space) SO components of M3Y and ATB forces become alike up to the range of momenta transferred $q \lesssim 3\ \mathrm{fm}^{-1}$, and the contribution to the cross section from TO components is insignificant because of their smallness, which explains the results obtained.

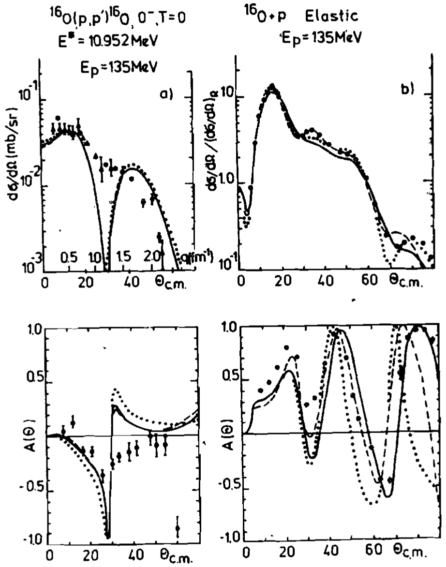

Fig.5. a) The cross sections for inelastic scattering $^{16}O(p,p')^{16}O$ *at* $E_p = 135$ *MeV calculated with* (np,nh) *wave functions, density-dependent effective forces and different optical potentials. b) The proton elastic scattering from* ^{16}O. *The meaning of the optical potential parameters:* ——— *CK* /18/, ... – *KA* /4/ *(version A),* – – – *KB* /4/ *(version B).*

Let us thoroughly discuss the results obtaines with the density dependent vG(100) effective forces. At $E_p = 80$ MeV calculations of the excitation of 0^- state in (p,n) reaction satisfactorily describe the experimental data (Fig.1). For (p,p′) reaction at $E_p = 135$ MeV calculations of the excitation of isoscalar 0^- state give a large dip around 30° absent in calculations with other forces and not observed experimentally (Fig.2). Experimental data on asymmetry are reproduced by density-dependent interactions better than by the density-independent ones. The use of other variants of optical potentials derived from the elastic scattering does not improve the description. The calculated results are only slightly sensitive to the choice of various phase-equivalent optical potentials (see Table 3 and Fig.5).

CONCLUSION

In this paper, we have studied isoscalar and isovector $0^+ \to 0^-$ transitions in (p,p′) and (p,n) reactions on ^{16}O nucleus in the energy range from 35 MeV to 135 MeV. Using the distorted-wave method with various effective NN-forces and wave functions we have computed the differential cross sections, analysing powers and analysed the available experimental data.

On the whole, we have obtained a satisfactory description for angular distributions and analysing powers. The disagreement between theoretical calculations and experimental data at momenta transferred $q > 1.5\ \mathrm{fm}^{-1}$ and low energies of incident protons may be related with the expected contribution from multistep processes.

Study of the role of various components of the effective force testified to an important role of the exchange terms for describing 0^--excitations. The choice of short-range odd components of effective NN-forces was found to be ambiguous. The use of density-dependent effective forces slightly changes the detailed picture of angular distributions, leaving the description of experimental data qualitatively unchanged.

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Гареев Ф.А. и др. E4-86-21

Исследование $0^+ \to 0^-$ переходов в реакциях $^{16}O(p,p')^{16}O$ и $^{16}O(p,n)^{16}F$ при $35 \leq E_p \leq 135$ МэВ

В рамках микроскопической версии DWIA проведен анализ расчетов дифференциальных сечений и анализирующих способностей для изоскалярных и изовекторных $0^+ \to 0^-$ переходов в реакциях $^{16}O(p,p')^{16}O$ и $^{16}O(p,n)^{16}F$. Было показано, что точный учет обменного выбивания в формфакторе и использование коррелированных (np, nh) волновых функций при построении ядерных переходных плотностей, улучшает описание рассматриваемых реакций при переданных импульсах $q \lesssim 1{,}5$ фм$^{-1}$, но сохраняет расхождение с экспериментом при больших q и $E_p = 35$ МэВ. При этом продемонстрирована неоднозначность выбора оптического потенциала, определяемого только из данных по упругому рассеянию. Селективность $0^+ \to 0^-$ переходов по отношению к эффективным NN-взаимодействиям позволяет анализировать вклады отдельных компонент этих сил, причем отмечена неопределенность, связанная с возможностью добавления произвольной δ-функции к их нечетным компонентам. Показано, что использование зависящих от плотности эффективных NN-сил улучшает описание как дифференциальных сечений, так и анализирующих способностей.

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Investigation of $0^+ \to 0^-$ Transitions in $^{16}O(p,p')^{16}O$ and $^{16}O(p,n)^{16}F$ Reactions at $35 \leq E_p \leq 135$ MeV

The calculation of differential cross sections and analysing powers for the isoscalar and isovector $0^+ \to 0^-$ transitions in $^{16}O(p,p')^{16}O$ and $^{16}O(p,n)^{16}F$ reactions has been analysed within the framework of the microscopic version of DWIA. It is shown that the theoretical description of the considered reactions at the transferred momenta $q \lesssim 1.5$ Fm^{-1} has been better when the exact knock-on terms are included in the form factor and the correlated (np, nh) wave functions are used for construction of the transition density. The discrepancy with experimental data for large q and $E_p = 35$ MeV was kept. The uncertainty of optical potential choice which is defined only from the inelastic scattering data is demonstrated. The selectivity of $0^+ \to 0^-$-transitions with respect to effective NN-interactions allows one to analyse contribution of separate components of these forces. In this way the uncertainty due to adding the δ-functions to the odd components is noted. It is shown that using the density dependent effective NN-forces improved the description of both differential cross sections and of analysing powers.

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

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