THE $^9Be(d,t)$ NUCLEAR REACTION AT LOW DEUTERON ENERGIES

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Consideration is given to the possibility of describing the experimental data, earlier obtained for angular dependences of cross sections and vector analyzing powers (VAP) of the $^9Be(d,t_0)$ reaction induced by vector polarized deuterons of energies between 2.5 and 2.8 MeV, within the framework of the distorted wave Born approximation (DWBA), using the "measured" optical potential parameters at input/output channels without additional variations. Pairs of sets of optical potential parameters have been found, which permit simultaneous fits of the main trends in the behavior of angular distributions of cross sections and the VAP for $^9Be(d,t_0)$. The direct pickup is demonstrated to be the predominant mechanism of the nuclear reaction occurrence at such low energies. It is possible that the characteristic properties of the direct process at so low energies are determined by the peculiarities of interaction between weakly coupled particles in the area of action of the thresholds of disintegration of the reacting nuclei into their fragments.

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1. INTRODUCTION

A number of experiments have been made in recent years to investigate the cross sections for deuteron-induced reactions on the ^9Be nucleus [1-2]. They provide a more systematic approach to the analysis of the mechanisms of nuclear reaction on this nucleus in a rather wide incident-deuteron energy range from 1 to 15 MeV.

The existing parameterizations of one-nucleon transfer calculations meet with difficulties stemming from the fact that apart from the direct process contribution, there arise competing mechanisms of the reaction occurrence, which distort the angular dependence shapes, of the measured observables in the experiment. This sets up the problem of finding the criteria for adequate description of the direct process in the low-energy region of incident particles that would be independent of a direct comparison with experimental observables. As already stated, the comparison may be distorted not only by contributions from indirect processes, but also by calculation errors due to violations of the conditions for the fulfillment of various assumptions included in the theoretical treatments of direct processes. Besides, there is also a problem connected with the divergence in the behavior of polarization observables such as the vector analyzing power (VAP) and the polarization of outgoing particles for the cases, where the cross-sectional angular dependences show distinct features typical of the direct process, this divergence being observed in a wide energy range.

A detailed analysis of cross-section angular distributions as functions of energy (see ref. [3]) as well as studies on optical potential parameterization (refs. [4, 5]) provide good basis for investigating the peculiarities of the angular distribution behavior of not only cross sections but also of polarization observables in deuteron-induced reactions on ^9Be at low energies. The unique feature of the chosen incident-deuteron energy range (1.5...3.0 MeV) lies in the fact that on the interval of less than 1 MeV there are two thresholds of target nucleus disintegration ($n-^8Be$ with $E_d^{lab} = 2.04\,MeV$, $\alpha-^5He$ with $E_d^{lab} = 3.01\,MeV$) and the threshold of incident deuteron disintegration ($n-p$ with $E_d^{lab} = 2.71\,MeV$).

The aim of the present work has been to clarify the possibility of simultaneous description of angular dependences of the cross section and the VAP in the framework of the DWBA, using a phenomenological parameterization of distorting wave functions in the input/output channels for the one-nucleon pickup reactions in the low-energy region of bombarding deuterons on the ^9Be nucleus. Our findings will be compared with the results obtained at other laboratories of the world.

2. SPECTRA FROM A TWO-LAYER TARGET

Simultaneous measurements of the differential cross section $d\sigma/d\Omega$ and the VAP $A_y(\theta)$ for elastic scattering of vector-polarized deuterons by ^9Be and ^{197}Au, and also, for the nuclear reactions $^9Be(d,p)^{10}Be$, $^9Be(d,t)^8Be$, $^9Be(d,\alpha)^7Li$ were performed by the method described in refs. [5, 6] with the use of

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two detectors, a two-component target and a polarized particle beam with one direction of the polarization vector. Figure 1 shows the charged particle spectrum measured at the interaction of polarized deuterons with a two-layer Be+Au target.

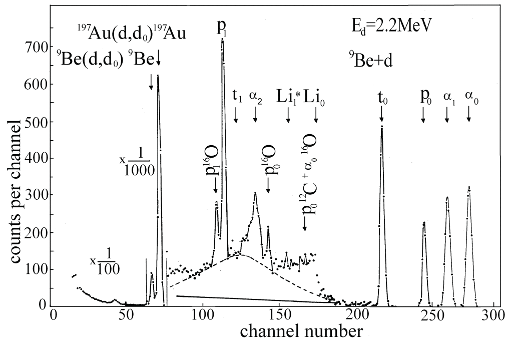

Fig.1. Charged particle spectrum measured at interaction of polarized deuterons with a two-layer (Be + Au) target at $\theta_l = 30°$ [6]

The charged particle spectra (see Fig.1) measured with the total deuteron energy resolutions $\Delta E_{1/2} = 50...70\,keV$ and $\Delta E_{1/2} < 40\,keV$ for the investigated (Be) and monitor (Au) parts of the two-layer target, respectively, have enabled us to separate the peaks of deuteron elastic scattering by ^9Be and ^{197}Au at $\theta_l \geq 30°$, and also, to separate clearly the peaks corresponding to the p_0, p_1, t_0, α_0, α_1 particle groups. This permits normalization of the yields of individual groups to the yield of elastic scattering by gold. The type of the particles and their energy groups were identified through calculations of the reaction kinematics: $E_b = f(E_a,\, E_x,\, \theta_b)$. The narrow peaks of p_1 and α_2, corresponding to the reactions $^9Be(d,p)^{10}Be^*$ ($E_x = 3.37\,MeV$) and $^9Be(d,\alpha_2)^7Li^*$ ($E_x = 4.63\,MeV$) lie on a wide ($\Gamma \sim 1\,MeV$) peak (t_1- dashed line) formed by a triton group from the reaction $^9Be(d,t_1)^8Be^*$ ($E_x = 2.94\,MeV$) and by the continuous alpha spectrum from the decay of ^8Be ground state in the reaction $^9Be(d,t_0)^8Be_{o.c.} \to 2\alpha$ (solid line). In the angular ranges $\theta_l = 100°...110°$ and $\theta_l = 140°...150°$, the triton peak t_0 overlaps with the proton peaks from the reactions $^{12}C(d,p_0)^{13}C$ and $^{16}O(d,p_0)^{17}O$, respectively. The technique of t_0 peak separation in the regions of overlap with the background has been described in ref. [7]. The t_1 group was not analyzed, as it was impossible to identify exactly the maximum value of the wide peak.

3. THE CROSS SECTION AND VECTOR ANALYZING POWER

Experimental results [7] for the angular dependence of the differential cross section are presented in Figs. 2 and 5, and the VAP energy dependence is shown in Fig.3. The VAP energy dependence for the $^9Be(d,t)^8Be$ reaction, measured at $\theta_1 = 30°$ in the region of forward-scattering angles that correspond to the pickup peak at energies higher than $2.0\,MeV$ ($A_y \approx 0$), and the VAP angular dependence for the $^9Be(d,t0)^8Be$ reaction (Fig.2) point t_0 the predominance of the direct process. The problem lies in the presence of the third maximum at these low energies and in the displacement of the main pickup peak, which corresponds to the transfer of the neutron having the orbital angular momentum $l = 1$, towards small angles (see Fig. 2).

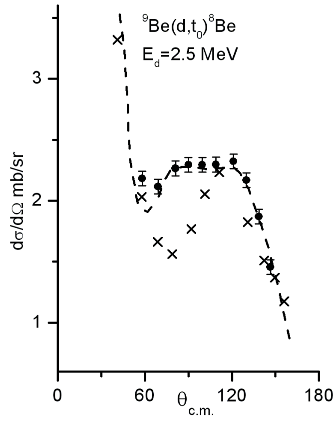

Fig.2. Comparison of our experimental data for the differential cross section with the data of other authors at $E_d = 2.5\,MeV$ for the $^9Be(d,t_0)^8Be$ reaction. • - our data; - - - - differential cross sections reconstructed with the Legendre polynomials coefficients taken from ref. [3]; × - data of ref. [8]

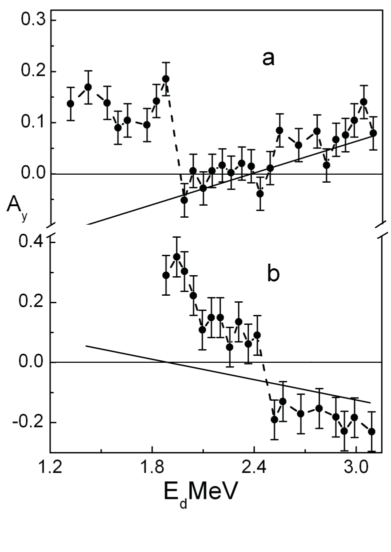

Fig.3. VAP energy dependence for the $^9Be(d,t_0)^8Be$ reaction, measured at $\theta_l = 30°$ (a) and $140°$ (b). Solid line represents the DWBA calculation with $D_2 + T_1$

The angular dependences of the cross section and the VAP at deuteron energy of $2.8\,MeV$ are shown in Fig. 5. They are similar to those observed at $E_d = 2.5\,MeV$.

4. DISTORTED WAVE ANALYSIS

For simultaneous analysis of the angular dependences of the cross section and VAP within the framework of the DWBA with the zero radius of interaction, we have used our own program [7,9]. The program was tested by comparing with DWUCK program computations for angular dependences of the cross-section and VAP of the $^9Be(d,t_0)^8Be$ reaction at the deuteron energy $E_d = 15\,MeV$ (Fig. 4) using the optical potentials of ref. [10]. The calculation in point is in good agreement with the experimental data for the $j_n = 3/2$ neutron pickup [10]. The pairs of sets of phenomenological potential parameters of the input and output channel for simultaneous description of the cross-section and VAP of the $^9Be(d,t_0)^8Be$ reaction with $j_n = 3/2$ were chosen through comparison of the zero-range DWBA

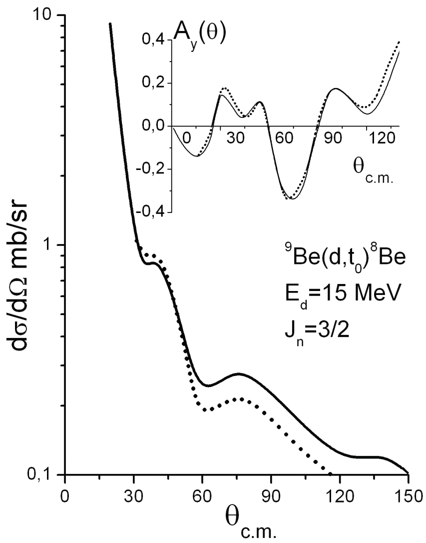

Fig.4. *Comparison of calculated angular distributions of differential cross sections and VAP for the one-nucleon pickup reaction $^9Be(d,t_0)^8Be$ at purely vector-polarized deuteron energy $E_d = 15\,MeV$. —- computation by our zero-range program in the [9]; $\cdot\cdot\cdot\cdot$ - DWUCK computation [10]*

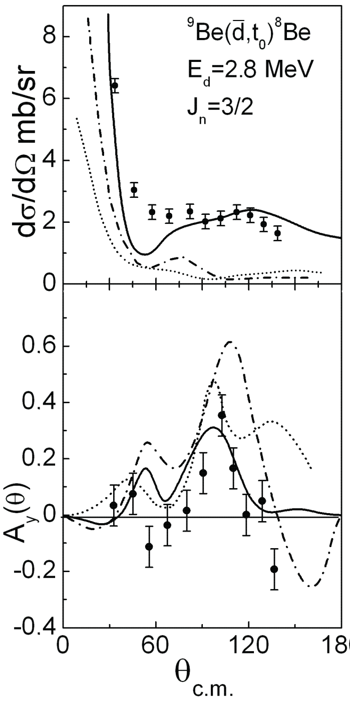

Fig.5. *Comparison of measured and zero-range DWBA-calculated angular dependences of cross-sections and VAP for the $^9Be(d,t_0)^8Be$ reaction at $E_d = 2.8\,MeV$ for $J_n = 3/2$, $S_t = 0.51$ and with different sets of optical parameters. $--$ - $PP1+T5$; $\cdot\cdot\cdot\cdot$ - $H'+T4$; $-\cdot--$ $P'+T4$*

calculated data with experimental angular distributions of the $d\sigma(\theta)/d\Omega$ cross-sections and VAP $A_e(\theta)$, using for this the purpose phenomenological sets of parameters, obtained at corresponding energies for deuterons: H', P', SH', PP' (see table 1) [5]; and tritons: $T1-T8$ (see Table 1).

Table 1. *Optical potential parameters with spin-orbital interaction for elastic deuteron scattering by ^9Be at $E_d \leq 2.8\,MeV$ [5]. Surface absorption $r_C = 1.3\,fm$*

E_d, MeV	*Set*	V_0 MeV	r_0, fm	a_0, fm	W_s MeV	r_w, fm	a_w, fm	V_{s0}, MeV	r_{s0}, fm	a_{s0}, fm	χ^2	$\chi^2_{c.-s.}$	χ^2_{pol}
2.8	H'	114.2	0.869	1.01	16.0	2.16	0.323	6.0	0.869	1.01			
2.8	P'	95.44	1.15	0.81	10.80	1.575	0.585	10.0	1.15	0.81			
5.25	D_2[14]	170.0	0.90	0.90	12.00	2.10	0.50	7.5	1.20	0.90			
2.8	$PP1$	95.44	1.15	0.79	10.80	1.70	0.585	10.0	1.15	0.60	3.8	3.34	4.22

Table 2. *Optical potential parameters for elastic scattering of helions and tritons, employed in the analysis of the $^9Be(d,t_0)^8Be$ reaction. Surface absorption $r_C = 1.4\,fm$*

Set	*particle*	E, MeV	V_0, MeV	r_0, fm	a_0, fm	W_s, MeV	W_v, MeV	r_w, fm	a_w, fm	$V_{s.o.}$, MeV	$r_{s.o.}$, fm	$a_{s.o.}$, fm	Ref.
$T1$			133.0	0.86	0.7	4.09	–	2.68	0.5	6.0	0.86	0.7	[16]
$T4$	$^3H+^9Be$	12.0	160.5	1.40	0.63	–	16.0	1.40	0.63	5.0	1.40	0.63	[3]
$T5$	$^3He+^9Be$		135.0	1.40	0.70	–	17.0	1.40	0.70	5.0	1.10	0.74	[15]

The calculation data and the measurement results are presented in Fig. 5. The calculated absolute differential cross sections are shown for the spectroscopic factor $S_n = 0.51$ (close to the theoretical value for the multiparticle shell model with the intermediate coupling - 0.58) [11].

The wave functions of the bound state of the ^9Be nucleus were calculated by a standard method using the Woods-Saxon potential with spin-orbital interaction. The parameters of the real part of the potential were $r_0 = r_{s0} = 1.25\,fm$ and $a_0 = a_{s0} = 0.65\,fm$ with $V_{s0} = 6.0\,MeV$.

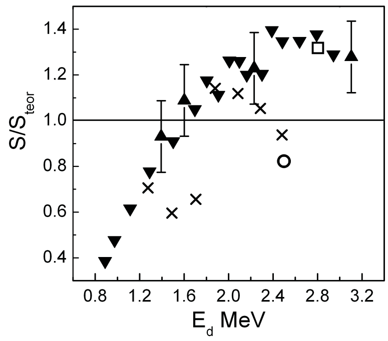

Fig.6. *Spectroscopic factors S/S_{theor}, $S_{theor} = 0.58$ [11]. black triangles - [3]; $\times$- [8], $\circ$ and square - present work*

The depth of the real part is found through variation until the binding energy of the neutron is obtained. The neutron binding energy, corresponding to the shell model with intermediate coupling [11] having the $\alpha + 5N$ structure, is equal to - 6.5 MeV, whereas for the one-particle model it equals 1.66 MeV with $V_0 = 38.65\,MeV$, just for which all the analysis data are shown.

Fig. 5 illustrates the possibility of simultaneous description of the cross-section and the VAP (experimentally observed at the incident deuteron energy $E_d = 2.8\,MeV$) are calculated with the spectroscopic factor close to the shell-model factor, without varying the experimentally measured parameters of optical potentials $PP1 + T5$. The $PP1$ potential describes the cross-section and the VAP of elastic scattering at $E_d = 2.8\,MeV$.

5. DISCUSSION OF ANALYSIS DATA

The mode of behavior of the VAP, calculated at $\theta_{c.m.} c.m. < 130°$, has the form corresponding to the calculations at deuteron energies higher than 12 MeV (see Fig. 4), and the differential cross section displays a double-humped structure in the intensity and position of their maxima. It should be noted that the deuteron potential parameters play an important role in the detailed description of angular distributions cross sections in the region of the pick-up peak, this having a pronounced effect on the spectroscopic factor value (increasing it by factors of 2 or 3 in this case). The set of the parameters $P' + T4$ is capable of quality reproducing both the VAP behavior pattern in the whole angular range and the correct cross-section in the region of the second peak, as it has been observed at $E_d = 3.6\,MeV$ in the work of Fulbright et al. [12].

Fig. 6 gives our calculated spectroscopic factors in comparison with the literature data. They are little different from the theoretical value given by the intermediate-coupling shell model [11].

In view of the foregoing it can be stated that in the low energy region the nuclear reaction $^9Be(d, t_0)^8Be$ proceeds mainly due to the mechanism of direct neutron pickup from the neutron-enriched surface of a weakly-bound nucleus. However, one should take into account the peculiarity in the behavior of the spectroscopic factor in the energy dependence of the differential cross-section in the region of the pickup peak maxima. The excitation function measured at $\theta_{lab} = 45°$ first shows a smooth rise up to a deuteron energy of 1.9 MeV, and from then on remains constant, i.e., after 2.0 MeV the pickup peak continues growing. Simultaneously, the second peak goes to splitting (see Fig. 3) accompanied by the displacement towards smaller angles, while the position of the third peak remains constant. In the foregoing we have shown that all the three peaks can be described in the framework of the DWBA.

6. CONCLUSIONS

The analysis of the $^9Be(d, t_0)^8Be$ reaction has demonstrated the possibility of describing the experimentally observed angular dependences of the differential cross-section and the VAP in the framework of the zero-rang DWBA, using for the purpose a modified in [5] set of the parameters $PP1$ (initial P') that describe elastic scattering at $E_d = 2.8\,MeV$, and also, the helion set parameters $T5$ at standard parameterization of the bound state. In such a case, the spectroscopic factor estimated from normalization of the calculated 1st-peak slope cross-section to the experiment ($\theta_{c.m.} \sim 30°$) (see Fig. 5) is in good agreement with the value calculated by the many-particle shell model with the intermediate coupling ($\alpha + 5N$) [11]. This situation may occur due to the fact that in spite of various restrictions arising at violations of DWBA theory approximations at low energies of the particle incident on the light nucleus and at a rather high $Q = 4.592\,MeV$, the neutron-binding energy is extremely low ($\varepsilon_n = 1.665\,MeV$) and this leads to the surface interaction of the reaction. Besides, the reaction proceeds in the incident deuteron energy region, which exhibits three disintegration thresholds of interacting nuclei ($n -^8 Be$ with $E_d^{lab} = 2.04\,MeV$, $\alpha -^5 He$ with $E_d^{lab} = 3.01\,MeV$ and $n - p$ with $E_d^{lab} = 2.71\,MeV$), and it is conceivable that this may also increase the contribution of the direct process.

The peculiarities of triton potential parameterization are the principal factors that determine the main features of the angular dependence of cross-sections and VAP. In our case, we have increased values of the radius parameter ($r_0 = 1.40\, fm$) and the depth of volume absorption ($W_v = 17.0\, MeV$). The deuteron potential parameters have an effect on the gradient of slope oscillations in the angular dependence of the cross section and the magnitude of the cross-section itself. Our parameterization enables one to reproduce the positions and values of the 1^{st} and 3^{rd} maxima in the angular distribution at low deuteron energies.

This mode of behavior of the cross-sectional angular distribution may point to the fact that the initial motion of the deuteron is little distorted during neutron transfer in the entire incident particle energy range. This may occur provided that the reaction has strictly a surface character. In the low energy region, this situation is of fundamental importance for the case when the matching condition is strongly violated for small r_i values ($r_a p_a = r_b p_b$, where p_i denotes relative momenta of the incident and outgoing particles, r_i corresponds to their relative distances from centers of the target nucleus and the residual nucleus).

The use of the parameterization D_2 for the reaction under study provides on the average a reliable fit of VAP energy dependences at $E_d > 2.0\, MeV$ [13] (see Fig. 3).

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ЯДЕРНАЯ РЕАКЦИЯ $^9Be(d,t)$ ПРИ НИЗКИХ ЭНЕРГИЯХ ДЕЙТРОНОВ

Н.А. Шляхов

Рассматривается возможность описания ранее найденных экспериментальных данных для угловых зависимостей дифференциальных сечений и векторных анализирующих способностей (ВАСП) реакции $^9Be(d,t_0)$, вызванных векторно поляризованными дейтронами с энергией $2,52...8$ МэВ, в рамках борновского приближения искаженных волн (БПИВ) с использованием "измеренных"параметров оптических потенциалов во входном и выходном каналах без дополнительных вариаций. Найдены пары наборов параметров оптических потенциалов, позволяющие одновременно воспроизвести основные тенденции в характере поведения угловых распределений сечений и ВАСП для $^9Be(d,t_0)$. Показано, что доминирующим механизмом протекания этих ядерных реакций при столь низких энергиях является прямой подхват. Возможно, что характерные черты прямого процесса при столь низких энергиях определяются особенностями взаимодействия слабо связанных частиц в области действия порогов развала ядер, участвующих в процессе, на их фрагменты.

ЯДЕРНА РЕАКЦІЯ $^9Be(d,t)$ ПРИ НИЗЬКИХ ЕНЕРГІЯХ ДЕЙТРОНІВ

М.А. Шляхов

Розглядається можливість опису раніше знайдених експериментальних даних для кутових залежностей диференціальних перерізів і векторних аналізуючих здібностей (ВАЗ) реакції $^9Be(d,t_0)$, викликаних векторно поляризованими дейтронами з енергією $2,52...8$ МеВ, в межах борнівського наближення збурених хвиль (БНЗХ) з використанням "виміряних"параметрів оптичних потенціалів у вхідному і вихідному каналах без додаткових варіацій. Знайдено пари наборів параметрів оптичних потенціалів, що дозволяють одночасно відтворити основні тенденції в характері поведінки кутових розподілів перетинів і ВАЗ для $^9Be(d,t_0)$. Показано, що домінуючим механізмом протікання цих ядерних реакцій при таких низьких енергіях є пряме підхоплення. Можливо, що характерні риси прямого процесу при таких низьких енергіях зумовлені особливостями взаємодії слабо зв'язаних частинок в області дії порогів розвалу ядер, що беруть участь у процесі, на їх фрагменти.