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Scattering and One Neutron Pick-Up Reaction on a ^{10}B Target with Deuterons at an Energy of 14.5 MeV

Nurzhan Saduyev ¹, Maulen Nassurlla ¹, Nassurlla Burtebayev ^{1,2}, Stanislav Sakuta ³, Marzhan Nassurlla ^{1,*}, Orazaly Kalikulov ^{1,2}, Romazan Khojayev ^{1,2}, Avganbek Sabidolda ¹ and Damir Issayev ^{1,2}

¹ Institute of Nuclear Physics, Ministry of Energy of Republic of Kazakhstan, Almaty 050032, Kazakhstan

² Department of Physics and Technology, Al-Farabi Kazakh National University, Almaty 050040, Kazakhstan

³ NRC “Kurchatov Institute”, Moscow 123182, Russia

* Correspondence: nassurlla@yahoo.com

Abstract: The elastic and inelastic scattering of deuterons on ^{10}B nuclei and the $^{10}\text{B}(d, t)^9\text{B}$ reaction were studied at a deuteron energy of 14.5 MeV. In inelastic scattering, differential cross-sections for transitions to ^{10}B states at excitation energies, E_x , of 0.718 MeV (1^+), 2.154 MeV (1^+), and 3.59 MeV (2^+) were measured. The cross-sections of the (d, t) reaction were measured for the ground ($3/2^-$) and excited states of the ^9B nucleus at $E_x = 2.361$ MeV ($5/2^-$) and 2.79 MeV ($5/2^+$). An analysis of the corresponding angular distributions was carried out using the coupled channel method. As a result of the calculations, the values of the quadrupole deformation parameters ($\beta_2 \approx 0.7 \pm 0.1$) for various transitions in the ^{10}B nucleus in inelastic scattering were extracted. From the analysis of the (d, t) reaction, the values of spectroscopic amplitudes ($SA = 0.67$ and $SA = 0.94$) for transitions to the states of the ^9B nucleus were extracted. The results obtained here, taking into account possible measurement errors, are in good agreement with the previously obtained data and the theoretical predictions.

Keywords: nuclear reactions $^{10}\text{B}(d, d)^{10}\text{B}$; $^{10}\text{B}(d, t)^9\text{B}$; deuteron beam energy of 14.5 MeV; measured spectra of deuterons and tritons; deduced reaction mechanism; $^{10}\text{B} + d$ optical potential parameters; deformation parameters; spectroscopic amplitudes



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1. Introduction

Single-nucleon transfer reactions induced by light ions have been established as a prominent tool in the field of nuclear spectroscopy. Following pioneering studies [1], a vast amount of research was carried out leading to the publication of a number of papers (see, e.g., [2–4] and the references therein). Reactions with light particles (p , d , ^3He and α) play a decisive role due to the simple and known structure of these particles.

Direct nuclear reactions with the simultaneous transfer of several particles in the form of a cluster are also widely used to obtain spectroscopic information.

Nuclear clustering is among the most interesting phenomena in nuclear physics, strongly affecting reaction dynamics. An example is the famous Hoyle state in ^{12}C , which is formed in stars by the fusion of three alpha particles [5]. Several studies have been dedicated to the investigations of clustering phenomena (see, e.g., [6–8] and the references therein). In a previous study [8], the effect of ^8Be transfer on elastic scattering was studied for the $^{20}\text{Ne}+^{28}\text{Si}$ system at energies of about 50 MeV, where both nuclei have a pronounced α -cluster structure. However, the large separation energies of ^8Be for these nuclei ($\epsilon > 12$ MeV) would seem to rule out this possibility.

The study of the elastic scattering of deuterons is also of great importance. Analysis of the corresponding angular distributions based on the optical model allows us to extract the values of the interaction potential parameters, knowledge of which is necessary to obtain data on the nuclear structure within the framework of certain reaction mechanisms.

However, it is known that the systematics of optical potentials at heavy nuclei are different from those in the light nuclei region (of the atomic mass of $A \leq 20$). This is largely explained by the more pronounced effects of the clustering of light nuclei. As a result, the role of exchange mechanisms with cluster transfer, physically indistinguishable from elastic scattering, increases. This leads to an anomalous increase in scattering cross-sections at large angles, which cannot be explained within the framework of the standard optical model. For the ^{10}B target, the behavior of the cross-sections can also be significantly influenced by spin-orbit interactions due to the large spin (3^+) of this nucleus. A systematic analysis of elastic scattering on p -shell nuclei was carried out in Ref. [9], with deuteron incident energies of between 5 and 170 MeV. The elastic scattering of deuterons, specifically on a ^{10}B target, was studied in Refs. [10–12] at energies of 11.8 MeV, 15 MeV, and 13.6 MeV, respectively.

Provided that the direct mechanism dominates, reactions of the (p, d) , (d, t) type with the pickup of one neutron are a good tool for studying hole states of nuclei. However, there is only scant information available about reactions starting from ^{10}B and ending in ^9B in comparison to those from neighboring nuclei. The (d, t) reaction on a ^{10}B target was previously studied at deuteron energies in the region of 12–18 MeV [10,11,13–15] and at an energy of 33.6 MeV [16].

These investigations were carried out more than 40 years ago. In these studies, the angular distributions of deuterons and tritons with transitions to the ground and excited states of ^{10}B and ^9B nuclei were studied. Based on distorted-wave Born approximation (DWBA) analysis, the values of the spectroscopic factors for transitions to the ground and first excited states of ^9B were extracted [10]. They turned out to be significantly less than the theoretical predictions of the shell model with intermediate coupling [17]. The reason for this may be due to the lack of a reliable optical potential for the interaction of tritons with ^9B nuclei in the output channel and the low energy of tritons from the (d, t) reaction ($Q = -2.18$ MeV) with a deuteron energy of 11.8 MeV [10]. It is also noteworthy that the analysis of this reaction did not consider the possible contribution of the exchange mechanism with the transfer of the ^8Be cluster in the $^{10}\text{B}(d, ^{10}\text{B})d$ reaction. Another aspect of the problem is that the ^{10}B nuclei, relating to the nuclei of the middle of the p -shell, have extremely high quadrupole deformation [18]. The deformation of the nucleus is reflected by the value of the nuclear quadrupole moment for ^{10}B ($Q = +84.72$ mb). In this case, when calculating cross-sections for the pickup reaction, it is necessary to consider the collective nature of nuclear states. This is supported by the results of studies of reactions (α, t) [19] and (d, t) on ^{11}B nuclei [20], where it was shown that taking into account the quadrupole couplings of the ground and excited states of nuclei strongly influences the cross-sections for reactions (α, t) and (d, t) .

In Ref. [21], the data for quasi-elastic scattering in the $^8\text{Li} + ^{90}\text{Zr}$ system at an energy of 18.5 MeV were described within the framework of the Coupled Reaction Channels (CRC) method, with the inclusion of couplings with excited states of the ^8Li and ^{90}Zr nuclei and the transfer reactions $^{90}\text{Zr}(^8\text{Li}, ^7\text{Li})^{91}\text{Zr}$ and $^{90}\text{Zr}(^8\text{Li}, ^9\text{Be})^{89}\text{Y}$. It was also shown that the coupling with the single-neutron stripping reaction has an important influence on the (quasi)elastic scattering of $^8\text{Li} + ^{90}\text{Zr}$ at this energy. Therefore, in this case, the CRC method is the most adequate for analysis.

In the current study, the elastic and inelastic scattering of deuterons by ^{10}B nuclei with excitation of the levels at 0.718 MeV (1^+), 2.154 MeV (1^+), and 3.59 (2^+) are investigated at an energy of 14.5 MeV. In addition, the reaction $^{10}\text{B}(d, t)^9\text{B}$ with transitions to the ground ($3/2^-$) and excited (2.361 MeV and 2.79 MeV) states of the ^9B nucleus was studied in more detail than in the previous study [10]. The main purpose was to obtain information on the role of the direct mechanism for a neutron pickup using the CRC method. Another task was to elucidate the connection between transitions in the (d, t) reaction with collective excitations of the ^{10}B nucleus.

2. Experimental Technique and Measurement Results

The measurements were performed on a 14.5 MeV deuteron beam extracted from the U-150M isochronous cyclotron of the Institute of Nuclear Physics (Almaty, Kazakhstan). The energy spread in the beam was about 150 keV.

The target was a self-supporting boron film that was 0.2 mg/cm^2 thick with a ^{10}B enrichment of 90%. Its thickness was determined from the energy loss of α -particles of a radioactive source with an accuracy of about 8%. The target was located in the center of a scattering chamber (Figure 1). The design of the chamber allowed us to perform measurements in the broad angular range (from 10° to 170° in the laboratory system) using telescopes with the following counters: T_1 , T_2 or T_3 (Figure 1). In our experiment, only one telescope of counters for each counter was used. Using telescope T_4 , it was possible to carry out measurements in the range of angles of $5\text{--}10^\circ$ in the laboratory system. The distance of the detectors from the target could be varied from 100 to 350 mm. The scattering chamber had a configuration that was specially designed (A in Figure 1) for taking measurements at small angles. A small-angle telescope (T_4) was positioned at a distance of up to 100 cm from the target. Regarding the total acceptance angle relating to the solid angle of the detector, the size of the beam spot and beam position stability was about 1.5° in the center mass system.

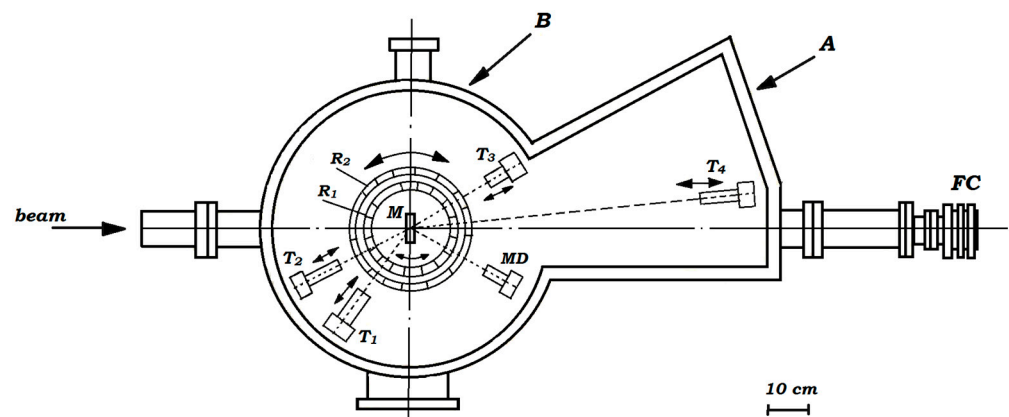


Figure 1. Scattering chamber. T_1 – T_4 denote telescopes; R_1 , R_2 —rings with the telescope’s holders; MD—monitor detector; FC—Faraday cup; A—chamber for measurements at small angles; B—scattering chamber; M—target.

A system of motors inside the chamber was used to carry out all the necessary movements, i.e., the replacement of the target, the angular and radial displacement of the telescopes, the change in the target plane orientation relative to the beam axis, etc.

The charged products of nuclear reactions were recorded using a counter telescope consisting of thin (ΔE) and thick (E) silicon detectors with thicknesses of about $50 \mu\text{m}$ and 2 mm , respectively. The separation of deuterons and triton from other charged particles was carried out via a two-dimensional analysis system (ΔE – E) using computer-aided measurement and control CAMAC-standard electronics and a processing program implemented on a personal computer. The overall energy resolution was mainly determined by assessing the energy spread in the beam. The absolute cross-sections were determined based on the known target thickness, the solid angle, and the beam current measured using a Faraday cup (FC in Figure 1). Part of a typical two-dimensional (ΔE – E) spectrum of particles from the $^{10}\text{B} + d$ interaction is presented in Figure 2, showing the separation of p , d , and t .

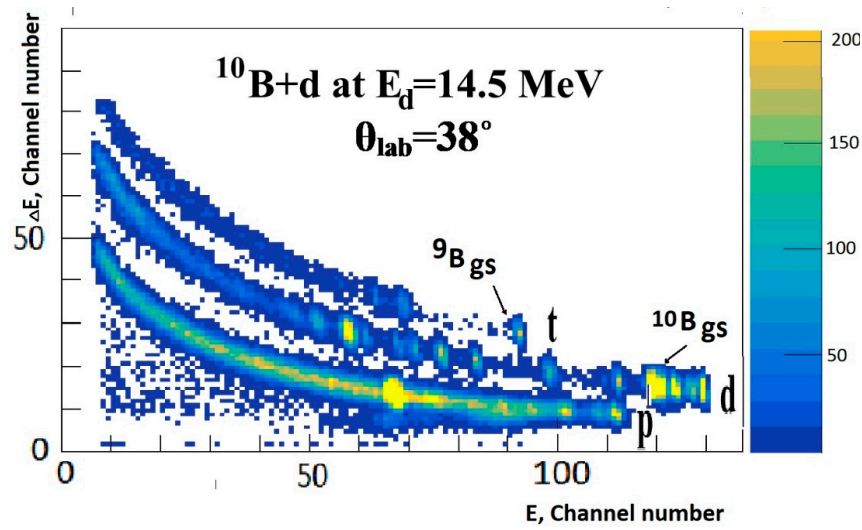


Figure 2. A part of a typical two-dimensional ($\Delta E-E$) spectrum of particles obtained in the interaction of deuterons with a ^{10}B target at the laboratory energy $E_{\text{lab}}(d) = 14.5$ Me and at the scattering angle $\theta_{\text{lab}} = 38^\circ$.

The examples of the spectra of deuterons scattered by ^{10}B and tritons from the reaction $^{10}\text{B}(d, t)^9\text{B}$, measured at an energy of 14.5 MeV, are shown in Figures 3 and 4, respectively. In the spectrum of deuterons (Figure 3), in addition to the elastic peak, there are transitions to the states at 0.718 MeV (1^+), 2.154 MeV (1^+), 3.59 (2^+), and 4.77 (3^+). All of them are connected to the ground 3^+ state of the ^{10}B nucleus by strong quadrupole ($E2$) transitions [22].

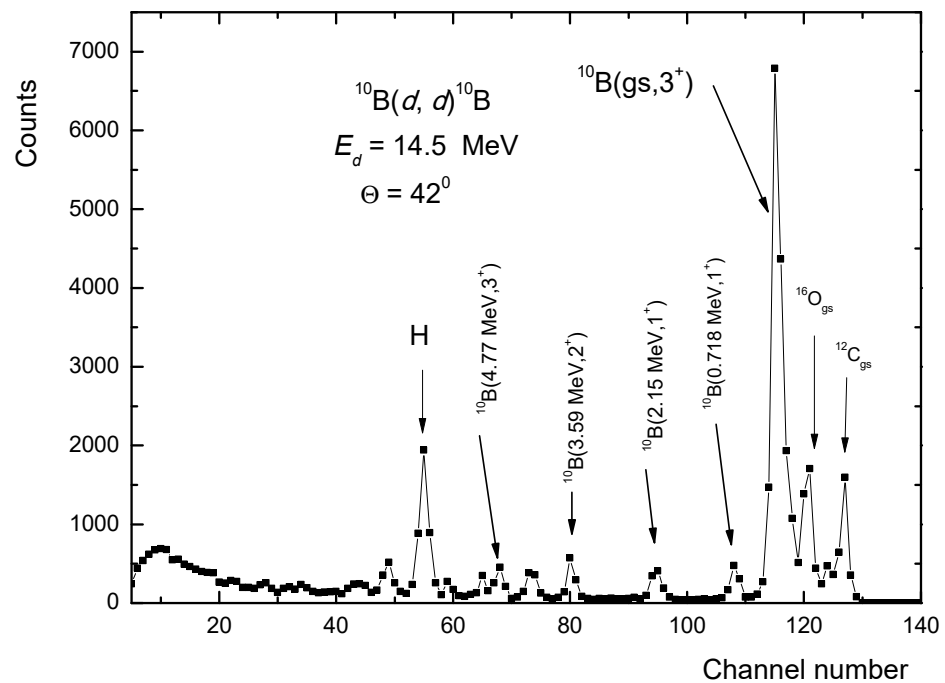


Figure 3. The energy spectrum of deuterons scattered by ^{10}B target measured at the angle of 42° and at an energy of 14.5 MeV.

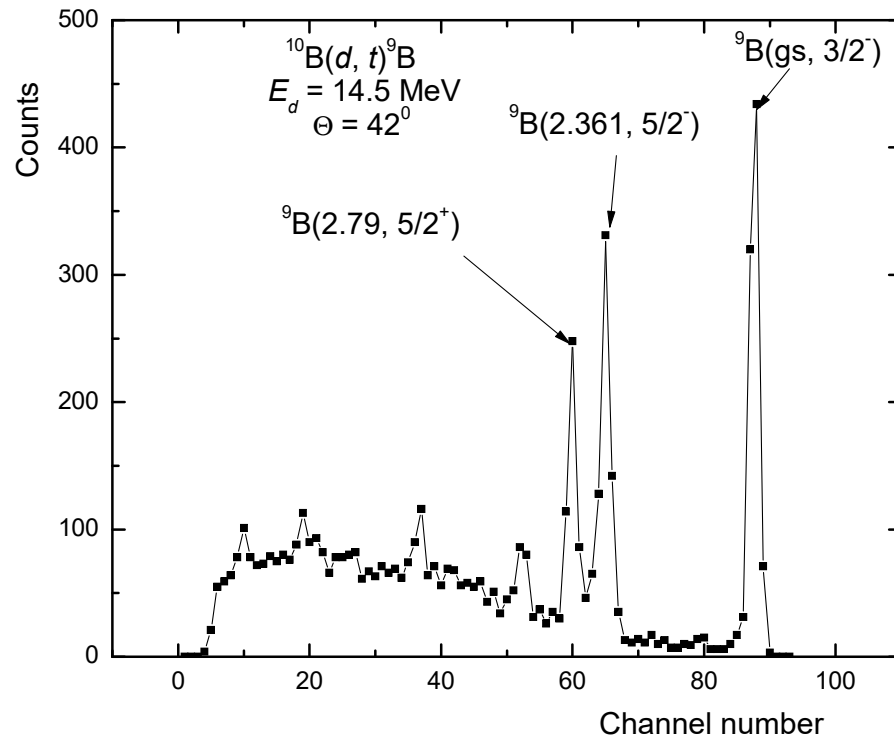


Figure 4. The triton energy spectrum from the $^{10}\text{B}(d, t)^9\text{B}$ reaction measured at $E_d = 14.5$ MeV and at the angle of 42° .

In the spectrum of tritons (Figure 4), along with an intense transition to the ground state ($3/2^-$) of the ^9B nucleus, a transition to the 2.361 MeV state ($5/2^-$) is observed. In addition, there is a peak corresponding to an excitation energy of 2.79 MeV. Here, the states ($5/2^+$) and ($1/2^-$) are known [22], which were not separated in our experiment. The $5/2^+$ level could not be excited in the reaction of neutron pickup from the $1p_{3/2}$ shell. Its excitation would indicate an admixture of the $2s1d$ shell in the ground state of ^{10}B .

The experimental angular distributions of deuterons scattered by ^{10}B with transitions to the states at 0.718 MeV (1^+), 2.154 MeV (1^+), and 3.59 MeV (2^+), and tritons from the reaction $^{10}\text{B}(d, t)^9\text{B}$ with transitions to the ground ($3/2^-$), and the excited states of ^9B at $E_x = 2.361$ MeV ($5/2^-$), and $E_x = 2.79$ MeV ($5/2^+$, $1/2^-$) are shown in Figure 5. As can be seen from the figure, the angular distributions of transitions to the ground ($J^\pi = 3/2^-$) and excited state ($5/2^-$) of the ^9B nucleus in the reaction (d, t) have a structure characteristic of neutron transfer with orbital angular momentum $l = 1$. The angular distribution for the peak corresponding to $E_x = 2.79$ MeV is very different from the corresponding distributions for the transitions of states 3.2^- and 5.2^- of the ^9B nucleus.

The systematic error of the measured cross-sections, according to our estimate, did not exceed 10%. The absolute cross-sections were determined based on the known target thickness (with the error not exceeding 8%), the solid angle of the telescope (error no more than 1%), and a beam current measured with a Faraday cup (with accuracy of 1%). When measuring in the region of the forward hemisphere, the statistical errors were about 1–5%. At larger angles, they increased, but never exceeded 15%.

The error bars shown in Figure 5 are smaller than the size of the experimental points.

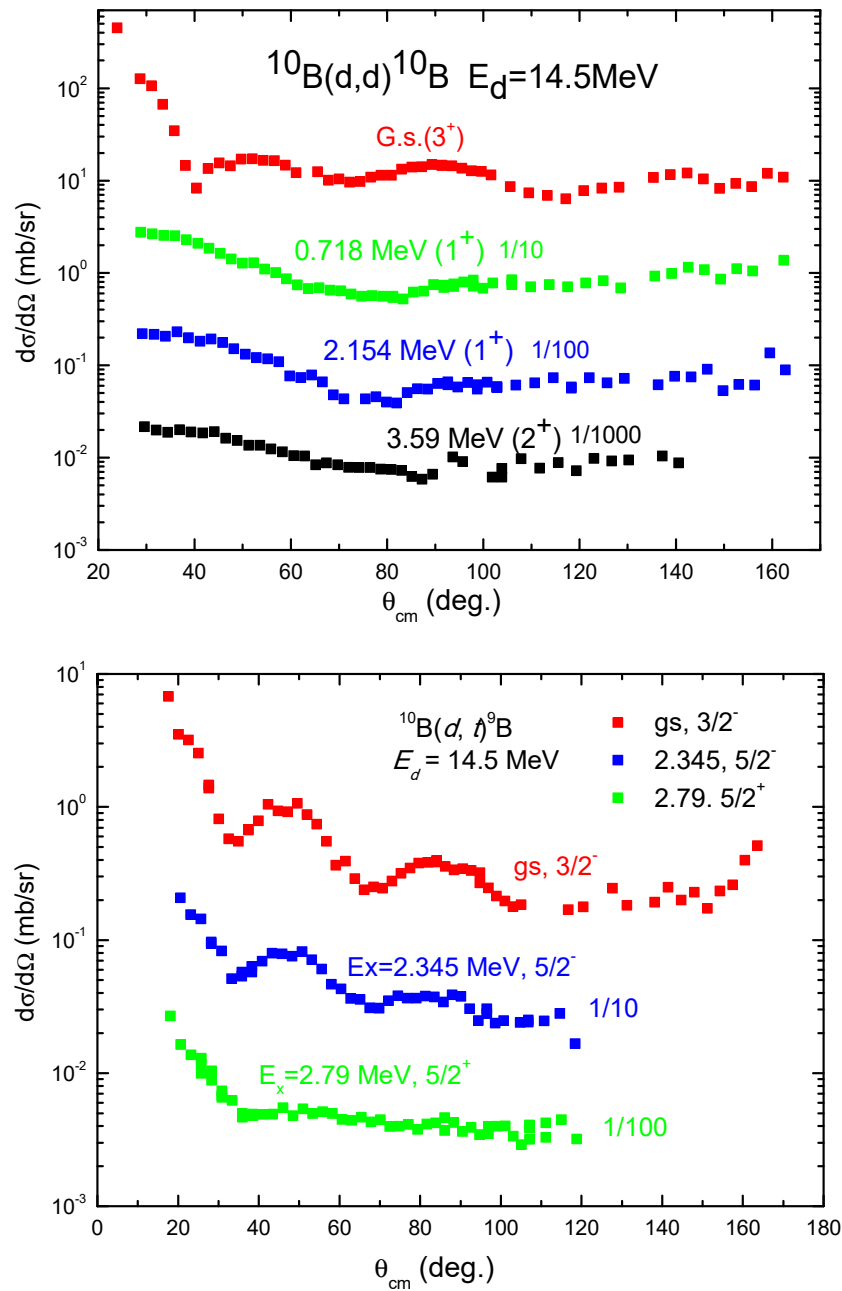


Figure 5. The angular distributions of deuterons scattered by ^{10}B (**upper**) and tritons from the reaction $^{10}\text{B}(d, t)^9\text{B}$ (**lower**) at an energy of 14.5 MeV.

3. Analysis of the Experimental Data and Discussion

3.1. Elastic Scattering

Most of the existing systematic deuteron potentials are based on the analysis of the angular distributions of the elastic scattering cross-sections of deuterons from heavy targets with $A \geq 30$. It is known that the systematics developed in such heavy-mass regions are different from that of the light-mass regions ($A \leq 20$). A systematic analysis of elastic scattering on p -shell nuclei was carried out in Ref. [9]. In the calculations, we used phenomenological Woods–Saxon potentials in the following form:

$$U(r) = -Vf(r) - iW_Vg(r) - W_S g'(r) - V_{so}h(r)(l\sigma) + V_C(r). \quad (1)$$

$V_C(r)$ is the Coulomb potential resulting from a uniform charge distribution of radius $1.3A^{1/3}$ fm. The calculations used potentials with both volume (W_V) and surface (W_S)

absorption, as well as the spin-orbit (V_{so}) potential. V denotes the depth of the real potential, l and σ denote the orbital moment and the spin of projectile, respectively.

In Equation (1), $f(r)$, $g(r)$, $g'(r)$, and $h(r)$ are the Woods-Saxon form factors:

$$f(r, r_v, a_v) = (1 + e^x)^{-1} \text{ with } x = (r - r_v A^{1/3}) / a_v,$$

$$g(r, r_w, a_w) = (1 + e^x)^{-1} \text{ with } x = (r - r_w A^{1/3}) / a_w,$$

$$g'(r, r_w, a_w) = (-4a_w) d/dr (1 + e^x)^{-1} \text{ with } x = (r - r_w A^{1/3}) / a_w,$$

$$h(r, r_{so}, a_{so}) = (\hbar/m_\pi c)^2 r^{-1} d/dr (1 + e^x)^{-1} \text{ with } x = (r - r_{so} A^{1/3}) / a_{so},$$

where a s and r s are the optical model potential (OMP) parameters for the corresponding form factors, c is the speed of light, and m_π represents the pion mass.

The OMP parameters are optimized with the minimization of the χ^2 -method:

$$\chi^2 = \frac{1}{N} \sum_{i=1}^N \left(\left[\sigma_i^{\text{exp}} - \sigma_i^{\text{th}} \right]^2 / \Delta \sigma_i^2 \right), \tag{2}$$

where σ_i^{exp} , σ_i^{th} , and $\Delta \sigma_i$ are the experimental and theoretical cross-sections and the experimental errors, respectively.

The fitting procedure was carried out with SPI-GENOA [23]. The starting values of the radii of the real and imaginary parts of the OMP for fitting to the optical model are taken from Ref. [24]. The OMPs used in our calculations are listed in Table 1.

Table 1. Potentials used in the entrance $^{10}\text{B} + d$ (A1, A2) and in the exit $^9\text{B} + t$ (B) channels. See text for details.

Pot.	V , MeV	a_v , fm	r_v , fm	$W_{V(S)}$, MeV	r_w , fm	a_w , fm	V_{so} , MeV	r_{so} , fm	a_{so} , fm	r_C , fm	σ_t , mb	χ^2	Ref.
A1	71.0	0.95	1.15	13.5	1.34	0.679	6.69	1.25	0.718	1.3	946	2.7	this work
A2	104.22	0.95	0.863	4.17 *	1.59	0.85	12.8	0.863	0.916	1.3	1070	4.9	[10]
B	141.2	0.758	1.156	16.4	1.535	0.99				1.3			[25]

* Surface absorption.

For the potential of the exit channel in the $^9\text{B} + t$ system, we used the potential found in Ref. [25] from the scattering of ^3He by ^9Be at an energy of 13.2 MeV.

A comparison of the calculated cross-sections for elastic scattering of deuterons by ^{10}B nuclei at an energy of 14.5 MeV is shown in Figure 6.

As can be seen, the calculation with potential A1 from Table 1 reproduces the experimental cross-sections quite well, whereas potential A2 (with surface absorption) gives underestimated cross-sections in the angle range of 45–75°.

3.2. The Coupled Channel Analysis

As is known, boron nuclei are highly deformed; thus, low-lying states are of a collective nature. In this case, the coupled channel method is most suitable for describing both scattering and reactions. Calculations were performed employing FRESKO code [26], with the potentials given in Table 1. But for a better agreement between the calculated cross-sections and the experiment, the depths of the imaginary potentials were reduced to values of 10.5 MeV and 3.17 MeV for potentials A1 and A2, respectively. The coupling scheme used in our calculations is shown in Figure 7.

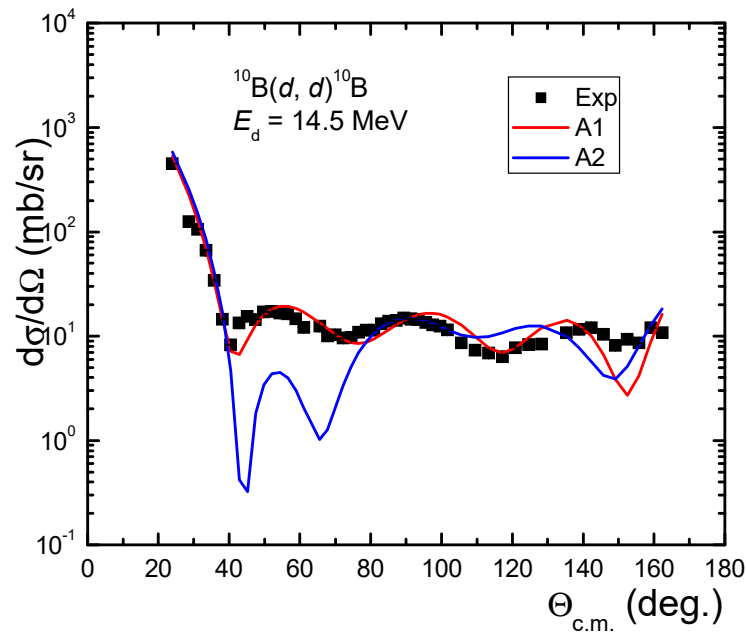


Figure 6. Elastic scattering of deuterons by ^{10}B nuclei at an energy of 14.5 MeV. The dots represent experimental data. Red and blue curves represent calculations with potentials A1 and A2 from Table 1, respectively.

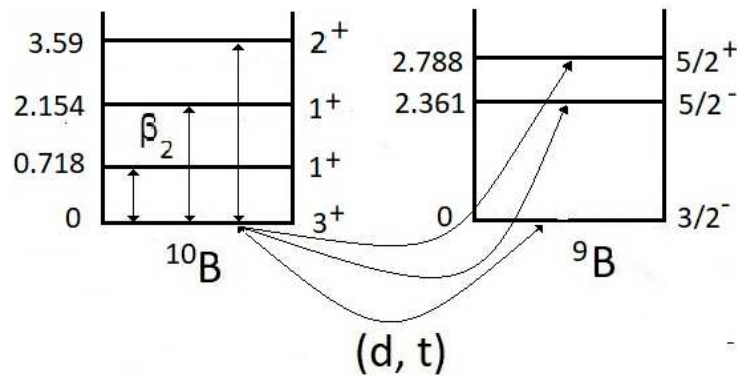


Figure 7. Coupling scheme used in calculations of deuteron scattering and the $^{10}\text{B}(d, t)^9\text{B}$ reaction. The bold two-headed arrows indicate quadrupole $E2$ transitions. The scheme includes direct reactions with transitions to the ground and excited states of the ^9B nucleus. β_2 is the quadrupole deformation parameter.

3.2.1. Inelastic Scattering

The inelastic scattering at $E_d = 14.5$ MeV with excitation of the ^{10}B states is interpreted within the frame of the collective model.

A comparison of calculated cross-sections with experimental data on elastic and inelastic scattering with transitions to states of ^{10}B at the excitation energy $E_x = 0.718$ MeV (1^+), 2.154 MeV (1^+) and 3.59 MeV (2^+) is shown in Figure 8. It can be seen that, taking into account that the channel coupling significantly improves agreement with the experimental data, both potentials (A1 and A2) from Table 1 reproduce the pronounced diffraction in the angular distribution of elastic scattering equally well over the entire range of angles. Calculations with potential A1 (red curves in Figure 8) also describe inelastic scattering quite well. But with potential A2 (blue curves in Figure 8), it is possible to achieve agreement with the experiment only at large angles (larger than 100°), while in the front hemisphere, the shape of the theoretical and measured cross-sections differs greatly.

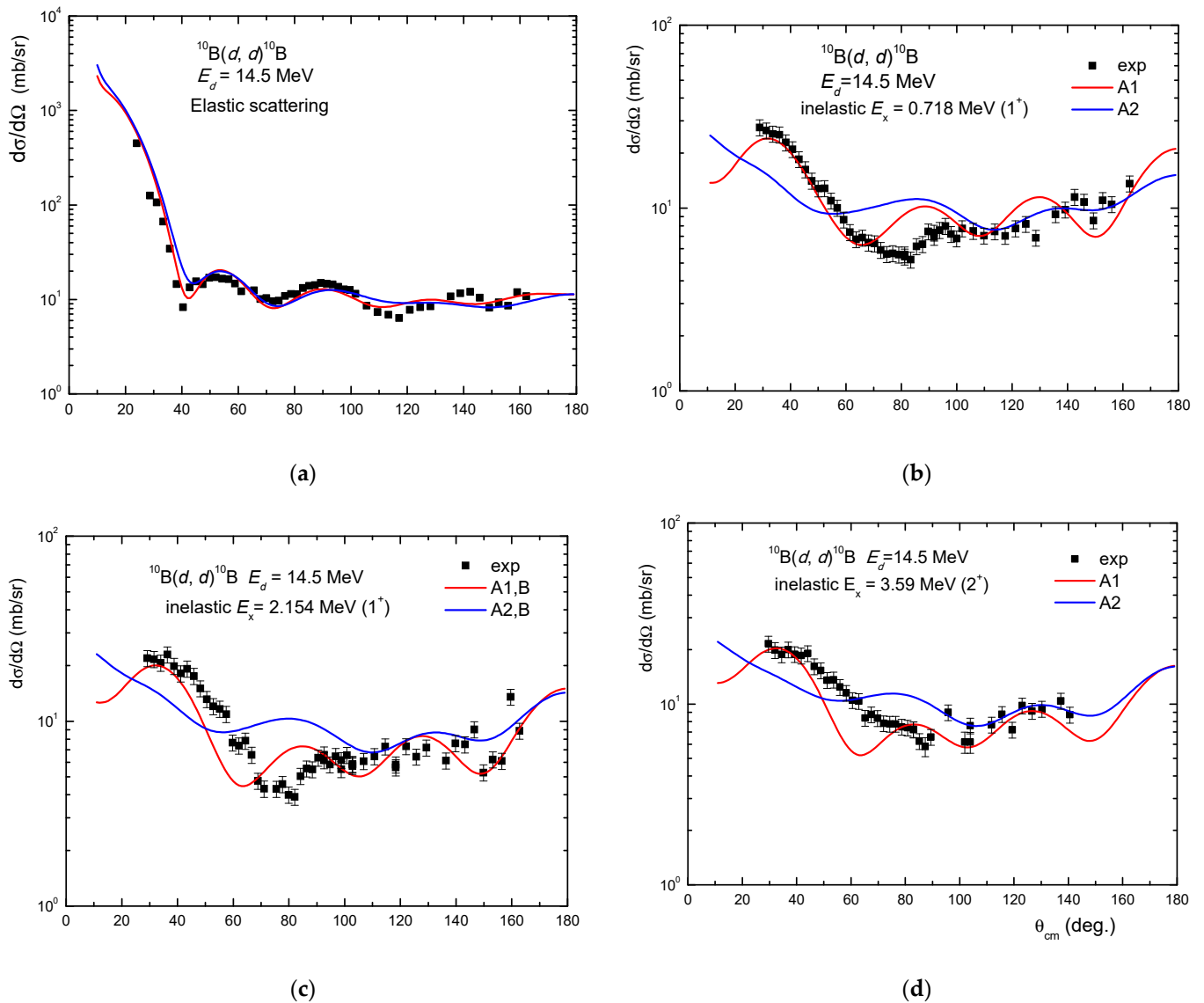


Figure 8. Angular distributions of elastic and inelastic scattering of deuterons by ^{10}B nuclei for transitions for the ground state (3^+) (a) and excited states at 0.718 MeV (1^+) (b), 2.154 MeV (1^+) (c) and 3.59 MeV (2^+) (d). The black dots represent experimental data. The red and blue curves represent calculations by the coupled channel method with potentials A1 and A2 from Table 1, respectively. The errors bars represent the statistical errors only.

Therefore, the deformation parameters β_2 were determined, with the potential A1 (red lines in Figure 8) from the condition of the best description of the experimental cross-sections, for the transitions to the 0.718 MeV (1^+), 2.154 MeV (1^+), and 3.59 MeV (2^+) states of ^{10}B at small angles in the first maximum of the angular distributions. For the above-noted transitions, the following values of quadrupole deformation parameters were obtained: $\beta_2 = 0.76 \pm 0.1$, $\beta_2 = 0.7 \pm 0.1$, and $\beta_2 = 0.7 \pm 0.1$, respectively. The above uncertainties include only statistical and systematic errors. As can be seen, the parameters of the β_2 extracted from the analysis also significantly depend on the choice of optical potential. This introduces additional uncertainty. The values obtained can be compared with the data from a study of inelastic scattering of protons with an energy of 30.3 MeV on ^{10}B nuclei with excitation of the same states of $\beta_2 = 0.67 \pm 0.04$, $\beta_2 = 0.49 \pm 0.04$, and $\beta_2 = 0.45 \pm 0.04$ [27,28]. Within the errors, the values of the quadrupole deformation parameters found by us are consistent with the results of previous analyses.

3.2.2. The (d, t) Reaction and the Role of Exchange Mechanism with Transfer of ^8Be

The coupled channel analysis, as shown in Figure 7, included elastic ($^{10}\text{B} + d$), inelastic scattering with excitation states of 0.718 MeV (1^+), 2.154 MeV (1^+), and 3.59 MeV (2^+), one-neutron pickup reactions with transitions to the ground ($3/2^-$), and excited states at 2.361 MeV ($5/2^-$) and 2.79 MeV ($5/2^+$). The reaction cross-sections were calculated using the coupled channel Born approximation model (incorporated in the FRESKO code [26]). The calculations were performed with potentials A1 or A2 for the entrance ($^{10}\text{B} + d$) channel and potential B for the exit ($^9\text{B} + t$) channel. The parameters of these potentials are given in Table 1.

The wave functions of bound states were calculated with the real Woods–Saxon potential at geometric parameters of $r_0 = 1.25\text{ fm}$ and $a = 0.65\text{ fm}$. Its depth was chosen so that the required binding energy of the transferred particle was obtained. A comparison of the calculated cross-sections with the experimental data is shown in Figure 9.

The spectroscopic amplitudes (SAs) used in our analysis are given in Table 2, along with theoretical predictions. Theoretical values for single-particle hole states in the $1p$ -shell excited in the pickup of a neutron from the ^{10}B nucleus were obtained within the framework of the shell model with intermediate coupling [17]. The SA for the $t \rightarrow d + n$ configuration was calculated in Ref. [29] using the translation-invariant shell model (TISM).

Table 2. Spectroscopic amplitudes (SAs) used in calculations of the $^{10}\text{B}(d, t)^9\text{B}$ reaction.

System	$E_x, \text{ MeV}$	J^π	nL_j	SA	SA Theory
$t \rightarrow d + n$	0.0	$1/2^+$	$1S_{1/2}$	1.22	1.22 [29]
$^{10}\text{B} \rightarrow ^9\text{B}^* + n$	0.0	$3/2^-$	$1P_{3/2}$	0.67 ± 0.1^a	-1.09 [17]
	2.361	$5/2^-$	$1P_{3/2}$	0.94 ± 0.2^a	-0.92 [17]
	2.788	$5/2^+$	$1S_{1/2}$		
$^{10}\text{B} \rightarrow ^8\text{Be} + d$	0.0	3^+	$1D_3$	0.8	0.811 [30]

^a SAs extracted in this analysis.

The errors in the extracted spectroscopic amplitudes in addition to statistics were determined by examining the uncertainties of the target thickness (less than 8%) and the uncertainty of normalizing the calculated cross-sections to the experimental data (less than 15%). Previously, the $^{10}\text{B}(d, t)^9\text{B}$ reaction was studied at deuteron energies of 11.8 MeV [10]. In Ref. [10], spectroscopic amplitudes of 0.89 and 0.8 were obtained for transitions to the ground and excited states of the ^9B nucleus. As can be seen from Table 2, the results found by us, taking into account possible errors, are in good agreement with the previously obtained experimental data and the theoretical predictions.

In addition to the direct neutron pickup, we assessed the role of the exchange mechanism with the transfer of the ^8Be cluster in the elastic scattering of deuterons on the ^{10}B nucleus. The calculations of the cross-sections for the exchange mechanism in this case are complicated by the fact that a heavy cluster (^8Be) can be transferred not only in its ground state but also in its excited states, and spectroscopic amplitudes are not known with sufficient accuracy. This leads to large uncertainties in the calculations. Therefore, for a rough estimate, only the ^8Be transfer in the ground state (0^+) was considered. Calculations were carried out with the potential A1 from Table 1, using the theoretical value of the spectroscopic amplitude calculated in Ref. [30] (see Table 2). The results of the calculations are shown in Figure 10.

It can be seen that the cross-sections for the exchange mechanism are more than two orders of magnitude smaller than the experimental values. Thus, one can well assume that the process of excitation does not play a significant role in the elastic scattering of deuterons and the (d, t) reaction.

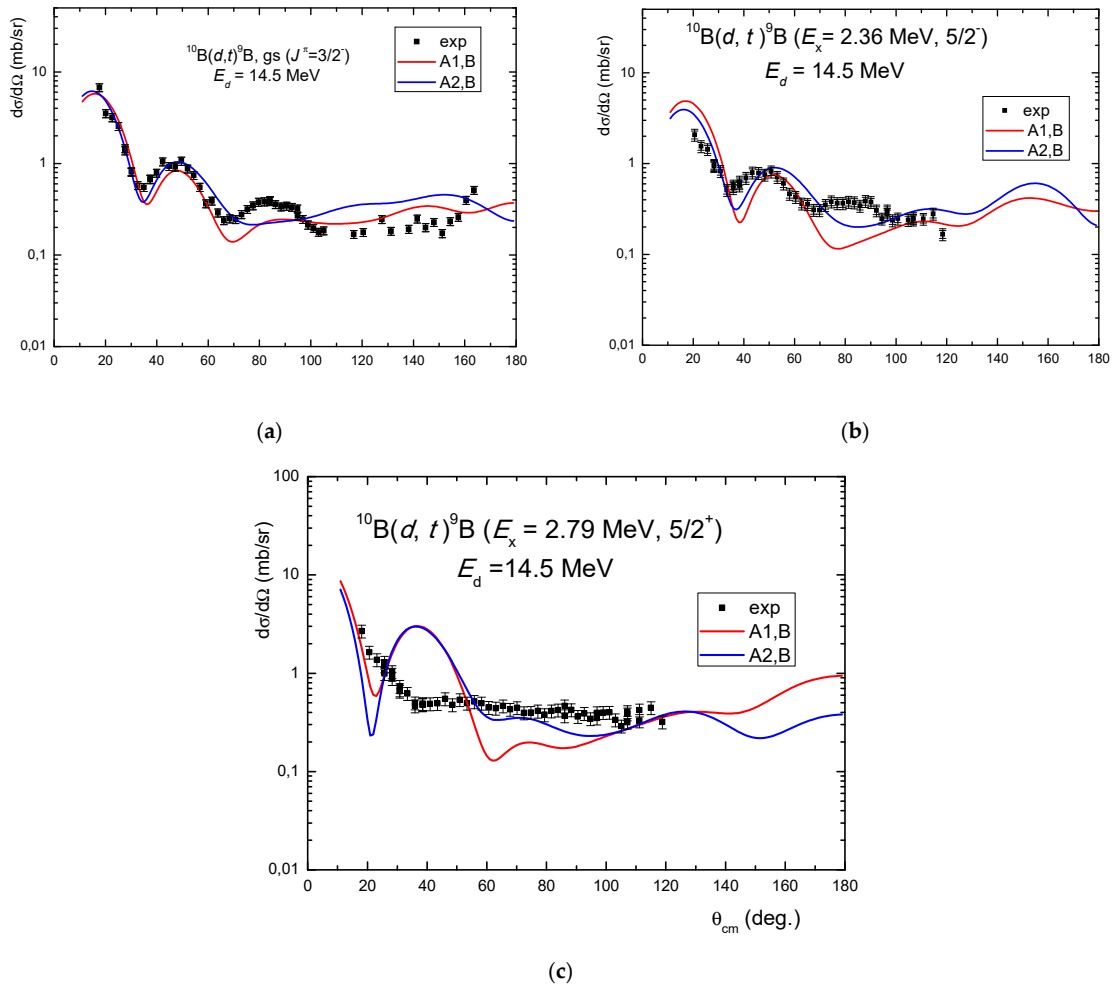


Figure 9. Angular distributions of tritons from the $^{10}\text{B}(d, t)^9\text{B}$ reaction for transitions to the ground ($3/2^-$) (a) and excited at 2.36 MeV ($5/2^-$) (b) and 2.79 MeV ($5/2^+, 1/2^-$) (c) states of ^9B nucleus. Points are experimental cross-sections. The red and blue curves represent calculations with A1, B and A2, B potentials from Table 1, respectively. The error bars represent the statistical errors only.

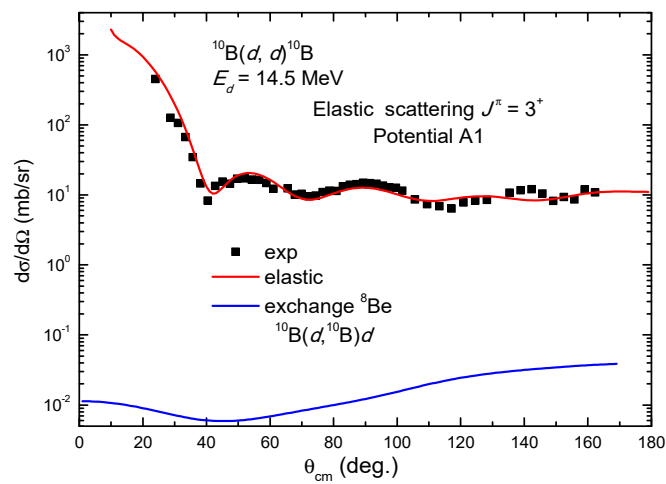


Figure 10. Angular distribution of deuterons elastically scattered by ^{10}B nuclei. The dots represent the experimental data. The red curve represents a calculation taking into account the mechanism of ^8Be cluster exchange in the $^{10}\text{B}(d, ^{10}\text{B})d$ reaction, which is physically indistinguishable from elastic scattering. The blue curve is calculation of $^{10}\text{B}(d, ^{10}\text{B})d$ reaction.

4. Conclusions

The elastic and inelastic scattering of deuterons on ^{10}B nuclei, as well as the $^{10}\text{B}(d, t)^9\text{B}$ reaction, were studied at a deuteron energy of 14.5 MeV. In deuteron scattering, in addition to elastic scattering, differential cross-sections for transitions to ^{10}B states were measured at excitation energies of 0.718 MeV (1^+), 2.154 MeV (1^+), and 3.59 MeV (2^+). The cross-sections of the (d, t) reaction were measured for the ground ($3/2^-$) and excited states of the ^9B nucleus at $E_x = 2.361$ MeV ($5/2^-$) and 2.79 MeV ($5/2^+$).

The optical potentials necessary for the analysis of experimental angular distributions were found from the best description of elastic scattering within the optical model. A good description of scattering over the full angular range was obtained. Further analysis of scattering and reaction (d, t) was carried out using the coupled channel method using the FRESKO program.

Analysis of inelastic scattering based on the collective model made it possible to extract a value of the quadrupole deformation parameter of about $\beta_2 = 0.7 \pm 0.1$ for transitions to various states of the ^{10}B nucleus. Within expected errors, the value obtained by us here is consistent with the results of a previous analysis focusing on the inelastic scattering of protons at an energy of 30.3 MeV.

Assuming a direct neutron pickup mechanism, a good enough description of the angular distributions for transitions to the ground ($3/2^-$) and first excited ($5/2^-$) states of the ^9B nucleus in the reaction (d, t) was obtained. The spectroscopic amplitudes of these transitions were extracted. The results obtained in the current study, within expected errors, are in quite well agree with the previously obtained experimental data and the theoretical predictions.

An estimate was made of the possible contribution to the elastic scattering of the exchange mechanism of the transfer of the ^8Be cluster in the $^{10}\text{B}(d, ^{10}\text{B})d$ reaction, which was physically indistinguishable from elastic scattering. It is shown that the exchange process is not significant.

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References

1. Butler, S.T. Direct nuclear reactions. *Phys. Rev.* **1957**, *106*, 272–286. [[CrossRef](#)]
2. Jones, K.L.; Adekola, A.S.; Bardayan, D.W.; Blackmon, J.C.; Chae, K.Y.; Chipps, K.A.; Cizewski, J.A.; Erikson, L.; Harlin, C.; Hatarik, H.; et al. The magic nature of ^{132}Sn explored through the single-particle states of ^{133}Sn . *Nature* **2010**, *465*, 454–457. [[CrossRef](#)] [[PubMed](#)]
3. Margerin, V.; Lotay, G.; Woods, P.J.; Aliotta, M.; Christian, G.; Davids, B.; Doherty, J.; Fallis, D.; Howell, O.S.; Kirsebom, D.J.; et al. Inverse kinematic study of the $^{26}\text{Al}(d, p)^{27}\text{Al}$ reaction and implications for destruction of ^{26}Al in Wolf–Rayet and asymptotic giant branch stars. *Phys. Rev. Lett.* **2015**, *115*, 062701. [[CrossRef](#)] [[PubMed](#)]
4. Schiffer, J.P.; Freeman, S.J.; Clark, J.A.; Deibel, C.; Fitzpatrick, C.R.; Gros, S.; Heinz, A.; Hirata, D.; Jiang, C.L.; Kay, B.P.; et al. Nuclear structure relevant to neutrino less double β decay: ^{76}Ge and ^{76}Se . *Phys. Rev. Lett.* **2008**, *100*, 112501. [[CrossRef](#)] [[PubMed](#)]
5. Hoyle, F. On nuclear reactions occurring in very hot stars. I. The synthesis of elements from carbon to nickel. *Astrophys. J. Suppl.* **1954**, *1*, 121–146. [[CrossRef](#)]
6. von Oertzen, W.; Freer, M.; Kanada-En'yo, Y. Nuclear clusters and nuclear molecules. *Phys. Rep.* **2006**, *432*, 43–113. [[CrossRef](#)]

7. Freer, M.; Horiuchi, H.; Kanada-En'yo, Y.; Lee, D.; Meißner, U.-G. Microscopic clustering in light nuclei. *Rev. Mod. Phys.* **2018**, *90*, 035004. [[CrossRef](#)]
8. Sgouros, O.; Soukeras, V.; Pakou, A.; Patronis, N.; Zerva, K.; Keeley, N.; Strojek, I.; Trzcińska, A.; Piasecki, E.; Rusek, K.; et al. Backward angle structure in the $^{20}\text{Ne} + ^{28}\text{Si}$ quasi-elastic scattering. *Int. J. Mod. Phys. E* **2013**, *22*, 1350073. [[CrossRef](#)]
9. Zhang, Y.; Pang, D.Y.; Lou, J.L. Optical model potential for deuteron elastic scattering with 1p-shell nuclei. *Phys. Rev. C* **2016**, *94*, 014619. [[CrossRef](#)]
10. Fitz, W.; Jahr, R.; Santo, R. Scattering and pick-up reactions with deuterons on Be, B, C, N and O at 11.8 MeV. *Nucl. Phys. A* **1967**, *101*, 449–459. [[CrossRef](#)]
11. Ludwig, E.J.; Busch, C.E.; Clegg, T.B.; Datta, S.K.; Watkins, A.C. The study of (d, t) and ($d, ^3\text{He}$) reactions in several 1p shell nuclei using vector-polarized beams. *Nucl. Phys. A* **1974**, *230*, 271–284. [[CrossRef](#)]
12. Zaika, N.I.; Mokhnach, A.V.; Nemets, O.F.; Semenov, V.S.; Tokarev, V.P.; Shmarin, P.L. Study of deuterons elastic scattering by ^{10}B and ^{12}C nuclei. *Yad. Fiz. [Sov. J. Nucl. Phys.]* **1975**, *21*, 460–463. (In Russian)
13. Fülle, R.; Netzband, D.; Schlott, K. Study of reaction $^{10}\text{B}(d, t)^9\text{B}$. *Nucl. Phys.* **1964**, *56*, 512–517. [[CrossRef](#)]
14. Zaika, N.I.; Kibkalo, Y.B.; Mokhnach, A.V.; Nemets, O.F.; Semenov, V.S.; Tokarev, V.P.; Shmarin, P.L. The (p, d) pick-up reaction on light nuclei. *Izvest. Acad. Nauk SSSR [Bull. USSR Acad. Sci.]* **1973**, *37*, 1073–1075. (In Russian)
15. Goncharov, S.A.; Mukhamedzhanov, A.M.; Romanovsky, E.A.; Valiev, G.E.; Gulamov, I.R.; Denisov, Y.I.; Iskhakov, T.; Karakhodzhaev, A.; Nie, G.K.; Yarmukhamedov, R.; et al. Spectroscopic Factors of ^9Be , ^{10}B and ^{13}C from (d, t) reactions. *Czechoslov. J. Phys. B* **1988**, *38*, 12–18. [[CrossRef](#)]
16. Kull, L.A.; Kashy, E. Study of Reactions $^{10}\text{B}(p, d)^9\text{B}$ and $^{11}\text{B}(p, d)^{10}\text{B}$. *Phys. Rev.* **1968**, *167*, 963–970. [[CrossRef](#)]
17. Cohen, S.; Kurath, D. Spectroscopic factors for the 1p shell. *Nucl. Phys. A* **1967**, *101*, 1–16. [[CrossRef](#)]
18. Bohr, A.; Mottelson, B.R. *Nuclear Structure*; World Scientific Co. Ltd.: Singapore. [[CrossRef](#)]
19. Burtebayev, N.; Sakuta, S.B.; Nassurlla, M.; Saduyev, N.; Nassurlla, M.; Sadykov, T.K.; Trzcinska, A.; Wolinska-Cichocka, M.; Khojaye, R. Mechanism of the $^{11}\text{B}(\alpha, t)^{12}\text{C}$ reaction at an energy of 40 MeV, role of exchange processes and collective excitations. *Eur. Phys. J. A* **2019**, *55*, 38. [[CrossRef](#)]
20. Nassurlla, M.; Burtebayev, N.; Sakuta, S.B.; Karakozov, B.K.; Nassurlla, M.; Burtebayeva, J.; Khojaye, R.; Sabidolda, A.; Yergaliuly, G. Deuteron scattering and (d, t) reaction on ^{11}B at an energy of 14.5 MeV. *Nucl. Phys. A* **2022**, *1023*, 122448. [[CrossRef](#)]
21. Pakou, A.; Keeley, N.; Pierroutsakou, D.; Mazzocco, M.; Acosta, L.; Aslanoglou, X.; Boiano, A.; Boiano, C.; Carbone, D.; Cavallaro, M. Important influence of single neutron stripping coupling on near-barrier $^8\text{Li} + ^{90}\text{Zr}$ quasi-elastic scattering. *Eur. Phys. J. A* **2015**, *51*, 90. [[CrossRef](#)]
22. Tilley, D.R.; Kelley, J.H.; Godwin, J.L.; Millener, D.J.; Purcell, J.E.; Sheu, C.G.; Weller, H.R. Energy levels of light nuclei $A = 8, 9, 10$. *Nucl. Phys. A* **2004**, *745*, 155–362. [[CrossRef](#)]
23. Perey, F.; (The Niels Bohr Institute, Copenhagen, Denmark). SPI-GENOA. An Optical Model Search Code. 1976; *Unpublished work*.
24. Daehnick, W.W.; Childs, J.D.; Vrcelj, Z. Global optical model potential for elastic deuteron scattering from 12 to 90 MeV. *Phys. Rev. C* **1980**, *21*, 2253–2274. [[CrossRef](#)]
25. Buffa, A.J.; Brussel, M.K. Elastic scattering of ^3He from ^9Be , ^{10}B , ^{11}B , ^{24}Mg , ^{25}Mg , ^{26}Mg and ^{27}Al . *Nucl. Phys. A* **1972**, *195*, 545–558. [[CrossRef](#)]
26. Tompson, I.J. Coupled reaction channels calculations in nuclear physics. *Comput. Phys. Rep.* **1988**, *7*, 167–212. [[CrossRef](#)]
27. de Swiniarski, R.; Resmini, F.G.; Glashauser, C.; Bacher, A.D. Study of ^{10}B by inelastic scattering of 30.3 MeV protons. *Helv. Phys. Acta* **1976**, *49*, 227–240. Available online: <https://www.e-periodica.ch/digbib/view?pid=hpa-001:1976:49::969#233> (accessed on 10 August 2024).
28. Ajenberg-Selove, F. Energy level of light nuclei. $A = 5-10$. *Nucl. Phys. A* **1979**, *320*, 1–224. [[CrossRef](#)]
29. Nemets, O.F.; Neudachin, V.G.; Rudchik, A.T.; Smirnov, Y.F.; Tchuvilsky, Y.M. *Nucleon Associations in Atomic Nuclei and Multi-nucleon Transfer Reactions*; Naukova Dumka: Kiev, USSR, 1988. (In Russian)
30. Rudchik, A.T.; Rudchik, A.A.; Muravynets, I.; Kemper, K.W.; Rusek, K.; Koshchy, E.I.; Piaseski, E.; Trzinska, A.; Pirnak, V.M.; Ponkratenko, O.A.; et al. $^7\text{Li}(^{15}\text{N}, ^{14}\text{C})^8\text{Be}$ reaction at 81 MeV and $^{14}\text{C} + ^8\text{Be}$ interaction versus that $^{14}\text{C} + ^8\text{Be}$. *Nucl. Phys. A* **2018**, *971*, 138–148. [[CrossRef](#)]

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