STUDY OF THE ^{7}Li$(d,t)^6$Li REACTION AT THE ENERGY OF 14.5 MeV*

N. Burtebayev[a,b], Zh.K. Kerimkulov[a], Maulen Nassurlla[a,b]
J.T. Burtebayeva[a,b], Marzhan Nassurlla[a,b], S.B. Sakuta[c]
T. Suzuki[d], K. Rusek[e], A. Trzcińska[e], M. Wolińska-Cichocka[e]

[a]Institute of Nuclear Physics, Almaty, Kazakhstan
[b]Al-Farabi Kazakh National University, Almaty, Kazakhstan
[c]National Research Center "Kurchatov Institute", Moscow, Russia
[d]Saitama University, Saitama, Japan
[e]Heavy Ion Laboratory, University of Warsaw, Warszawa, Poland

(Received January 23, 2019)

Angular distributions of scattered deuterons on ^{7}Li nuclei with excitation of the 0.478 MeV ($J^\pi = 1/2^-$) level and tritons from the ^{7}Li$(d,t)^6$Li reaction with transitions to the ground (1^+) state of ^{6}Li were measured at 14.5 MeV. Analysis of the experimental data was performed in the framework of the optical model and the coupled reaction channels method with taking into account the α- and n-transfer mechanisms. The values of the spectroscopic factors and the deformation parameters for the ^{7}Li, ^{6}Li were extracted.

DOI:10.5506/APhysPolB.50.703

1. Introduction

As it is well-known, attempts to describe the scattering and nucleon transfer reactions between the light nuclei are often failed in the frameworks of the simple optical model and conventional DWBA [1]. The reason is small amount of target nucleons and cluster effects, which become apparent as an anomalous large-angle scattering. The nature of this phenomenon for the lithium nuclei can be stipulated for their pronounced $(\alpha + d)$ and $(\alpha + t)$ cluster structure [2]. Moreover, in connection with the problem of nucleosynthesis of light nuclei, the reactions with lithium were studied extensively in 70s, but consecutive analysis of their mechanisms and obtaining the correct spectroscopic information has been carried out in the last decade [1, 3, 4].

* Presented at the Zakopane Conference on Nuclear Physics "Extremes of the Nuclear Landscape", Zakopane, Poland, August 26–September 2, 2018.

The ^{7}Li$(d,t)^6$Li reaction with the production of tritium is of particular interest for applications [5]. The (d,t) reaction on ^{7}Li nuclei was previously studied at 12 MeV [6, 7], 15 MeV [8, 9], 18 MeV [10], 20 MeV [11], 25 MeV [1] and 28 MeV [12] energies. The measurements in the full angular range were done at $E_d = 12$ MeV and 25 MeV [1, 6] only. In other cases, they were performed in the forward hemisphere. The standard DWBA with zero and finite-range interaction, used in the calculation of the angular distributions in [6, 7], does not describe the experimental cross sections at large angles.

This work is intended to trace the energy dependence of pick-up of one neutron in the reaction ^{7}Li$(d,t)^6$Li in totality with [1], where the calculations were made taking into account the α-cluster exchange mechanism in the framework of the coupled reaction channels (CRC) method.

2. Experimental setup

The experiment was performed using the deuteron beam with energy of 14.5 MeV, extracted from the U-150M isochronous Cyclotron of the Institute of Nuclear Physics (Almaty, Kazakhstan). Differential cross sections for elastic and inelastic scattering of deuterons and tritons from the (d,t) reaction on ^{7}Li nuclei were measured in the angular range from 18° to 128° (lab). Experimental errors not exceeded 8%. The metal lithium with 90% enrichment of ^{7}Li was used as a target. It was manufactured by thermal evaporation of lithium on a thin alundum (Al_2O_3) film (30 mg/cm^2) in vacuum. After deposition, the target was transferred to a scattering chamber without breaking the vacuum. The thicknesses of lithium layers, determined by the energy losses of α-particles from a radioactive source, were about 0.4 mg/cm^2. The design of the scattering chamber is described in detail in [13]. Deuterons and tritons were (see Fig. 1) detected and identified using the ΔE–E telescope of two silicon counters with thicknesses of 30–100 mi-

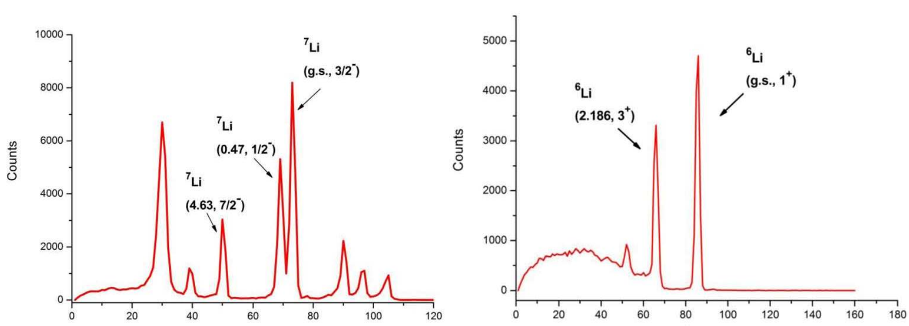

Fig. 1. Typical energy spectra of scattered deuterons on ^{7}Li (left) and tritons from ^{7}Li$(d,t)^6$Li reaction (right) measured at $\theta_{\rm lab} = 70°$ and $\theta_{\rm lab} = 36°$, respectively.

crons (ΔE detector) and 2 mm (E detector). The total energy resolution was around 150 keV. It was determined mainly by energy spread of the beam and target thickness.

3. Analysis and discussion

The ^{7}Li nucleus has a weakly bound structure $^7\mathrm{Li} = \alpha + t$ and, in this case, the exchange mechanism with α-particle transfer ^{7}Li(d,^{6}Li)t can give a significant contribution to the cross section of the ^{7}Li(d,t)^{6}Li reaction in the rear hemisphere. This effect for the ^{7}Li(d,t)^{6}Li reaction was investigated very carefully in [1] at the energy of 25 MeV. Therefore, the calculation of the cross sections for the deuteron scattering and the ^{7}Li(d,t)^{6}Li reaction was carried out in the framework of the coupled reaction channels which was presented in a similar manner as in the article [1] via the FRESCO [14] code using potentials found from the analysis of the elastic scattering.

Only the one-step processes with neutron pick-up and the α-particle cluster transfer ^{7}Li(d,^{6}Li)t were taken into account. The coupling scheme is shown in Fig. 2. The system of nine nucleons presented in the entrance channel as $^7\mathrm{Li} + d$ was replaced by three subsystems

$$\mathrm{I.} \quad d+^7\mathrm{Li}\,; \qquad \mathrm{II.} \quad t+^6\mathrm{Li}\,; \qquad \mathrm{III.} \quad ^6\mathrm{Li}+t\,. \tag{1}$$

All states of subsystems II and III are coupled with subsystem I by the reactions with neutrons and α-particles transfers. Couplings between ground and excited states of nuclei ^{7}Li and ^{6}Li were calculated using the rotational model with the form factor for quadrupole transitions ($\lambda = 2$).

$$V_\lambda(r) = \frac{\delta_\lambda}{\sqrt{4\pi}} \frac{\mathrm{d}U(r)}{\mathrm{d}r}\,. \tag{2}$$

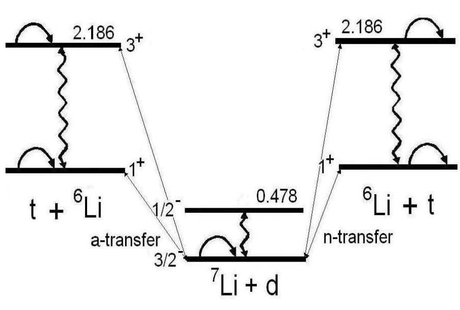

Fig. 2. The coupling scheme used in the CRC calculations for the ^{7}Li(d,t)^{6}Li reaction. The arcs show the spin reorientations of ^{7}Li and ^{6}Li nuclei in ground and excited states.

The prior representation of DWBA with a finite range interaction, incorporated in the FRESCO code, was used in the calculations of neutron and α-particle transfer reactions. So, in the CRC analysis, the $^7\mathrm{Li} + d$ elastic and inelastic scattering with the transitions to the ground and first excited states of ^{6}Li and ^{7}Li, spin reorientations of ^{6}Li, ^{7}Li as well as one-step α- and n-transfer reactions were included in the channels coupling scheme. The wave functions of the bound states of $^7\mathrm{Li} \rightarrow ^6\mathrm{Li} + n$, $^7\mathrm{Li} \rightarrow \alpha + t$, $^6\mathrm{Li} \rightarrow \alpha + d$ and $t \rightarrow d + n$ were calculated in a standard way by fitting a depth of the real part of the Woods–Saxon potentials, giving the known binding energy ("well-depth" procedure). Geometric parameters of the potentials (radii and diffuseness) were used the same as given in [1] and were fixed. As starting, the optical potentials (OP) [1] for the input $d+^7$Li and output $t+^6$Li channels obtained from analysis of the elastic scattering of d and ^{3}He on ^{7}Li and ^{6}Li nuclei respectively, at the incident particle energies in the range of 25–35 MeV [3, 5, 15, 16] were used.

The best description of the experimental data for the elastic scattering $^7\mathrm{Li}(d,d)^7\mathrm{Li}$ gives the set 4 from [1] (see table in article [1]). However, in our case, the depths of the real parts of the potentials have been increased to values $V_0(^7\mathrm{Li}+d) = 89.5$ MeV and $V_0(^6\mathrm{Li}+t) = 191.0$ MeV. The calculated cross sections for the elastic and inelastic scattering with excitation of the $E_x = 0.478$ MeV $(1/2^-)$ level of the ^{7}Li nucleus are presented in Fig. 3 (left). It can be seen that the CRC calculations describe well the experimental cross sections in full angular range for the elastic scattering $^7\mathrm{Li}(d,d)^7\mathrm{Li}$.

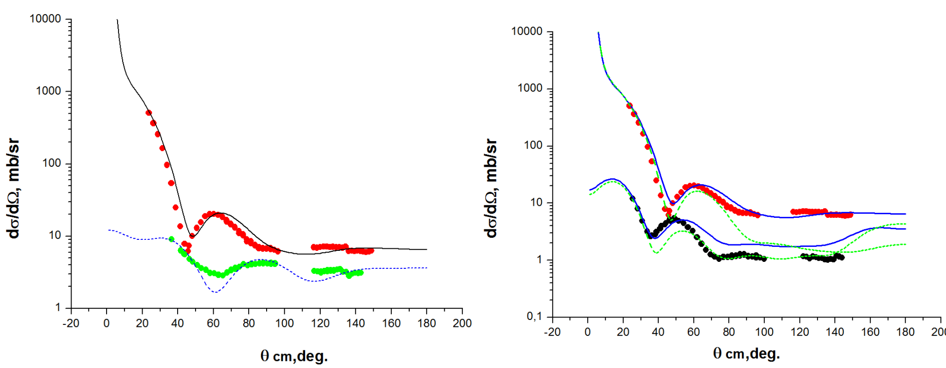

Fig. 3. (Colour on-line) The angular distributions for elastic and inelastic ($E_x = 0.478$ MeV, $1/2^-$) scattering of deuterons on ^{7}Li nuclei (left) and for tritons from the $^7\mathrm{Li}(d,t)^6\mathrm{Li}$ reaction (right) at the beam energy of 14.5 MeV. The solid points are experimental data. The curves represent results of the CRC calculations with the potentials from Table I. Left: the solid (black) and dashed (blue) lines are the CRC calculations with $W_D(^7\mathrm{Li}+d) = 6.7$ MeV. Right: the CRC calculations with $W_D(^7\mathrm{Li}+d) = 12.7$ MeV (dashed (green) lines) and $W_D(^7\mathrm{Li}+d) = 6.7$ MeV (solid (blue) lines).

It should be noted that the initial parameters of the potentials of set 4 [1] used in this calculations were slightly changed because the current energy of the incident deuterons is significantly less comparing with 25 MeV given in [1]. With decreasing energy, the depth of the real part of the potential is increasing. So two parameters were subjected to change — the depths of real parts for the $^7\mathrm{Li} + d$ channel ($V_0 = 89.5$ MeV) and the $^6\mathrm{Li} + t$ channel ($V_0 = 191$ MeV) to fit the elastic scattering $^7\mathrm{Li}(d, d)^7\mathrm{Li}$. In order to achieve agreement between the cross sections calculated at large angles with the measured cross sections, the depth of the imaginary potential was reduced to the value $W_D = 6.7$ MeV for $^7\mathrm{Li}(d, d)^7\mathrm{Li}$ reaction. The potentials used in the calculations are shown in Table I, where r_i and a_i are the reduced radii and diffuseness's of real (V), imaginary (W) and real spin–orbit (so) potentials.

TABLE I

Optical potentials used in the CRC calculations of the scattering and $^7\mathrm{Li}(d, t)^6\mathrm{Li}$ reaction cross sections at $E_d = 14.5$ MeV.

Channel	V_0 [MeV]	r_V [fm]	a_V [fm]	$W*_{V/D}$ [MeV]	r_W [fm]	a_W [fm]	V_so [MeV]	r_so [fm]	a_so [fm]
$^7\mathrm{Li} + d$	89.5	1.24	0.74	12.7D	1.24	0.74	10.44	0.82	1.05
$^6\mathrm{Li} + t$	191.0	1.11	0.69	17.0V	1.39	0.59	1.72	1.36	1.18

$*\,V/D$ — potential with volume and surface absorption, respectively.

As for the $^7\mathrm{Li}(d, t)^6\mathrm{Li}$ reaction, the calculations were carried out using the potential given in Table I. A comparison of the calculated cross sections with the experimental data is shown in Fig. 3 (right). The calculations give fairly good description of the measured differential cross sections at large angles with taking into account the contribution of α-transfer mechanisms to the scattering process.

To sum up, the potential from Table I (the grey/green lines in Fig. 3 (right)) describes quite well the experimental data on $^7\mathrm{Li}(d, t)^6\mathrm{Li}$, but does not fit the elastic scattering $^7\mathrm{Li}(d, d)^7\mathrm{Li}$. At the same time, the potential with $W_D = 6.7$ MeV (the blue lines in Fig. 3 (right)) describes very well the elastic scattering $^7\mathrm{Li}(d, d)^7\mathrm{Li}$, but does not the $^7\mathrm{Li}(d, t)^6\mathrm{Li}$ reaction.

The deformation lengths (δ_2) and spectroscopic factors (SF) extracted from the analysis are shown in Table II. The spectroscopic factor of $^6\mathrm{Li} = \alpha + d$ was taken from [17]. As a result, the SFs for $\alpha + t$ and $n+^6\mathrm{Li}$ configurations of ^{7}Li have been obtained (see Table II) from the analysis. The analysis of the data at the forward hemisphere was carried out using the modified DWBA method as it was made in [3] for obtaining the asymptotical normalization coefficient for the $^7\mathrm{Li}_\mathrm{gs} =^6 \mathrm{Li} + n$ configuration. The contribution of one-step neutron pick-up was evaluated by matching the SFs for this configuration extracted from the ordinary DWBA analysis and the CRC method. The values of the deformation parameters for ^{7}Li and ^{6}Li ($\delta_2 = 4.0$ and 3.0, respectively) as well as spectroscopic factors (SF) extracted in this analysis are in good agreement with the results obtained in [1] and with theoretical calculations within the framework of the translational invariant shell model [17].

TABLE II

Deformation lengths (δ_2) and spectroscopic factors (SF).

δ_2 [fm]		System	SF	System	SF	System	SF
^{7}Li	^{6}Li	$t \to d + n$	1.5	$^6\mathrm{Li} \to a + d$	1.35	$^6\mathrm{Li}* \to a + d$	0.44
4.0	3.0	$^7\mathrm{Li} \to ^6\mathrm{Li} + n$	0.77	$^7\mathrm{Li} \to ^6\mathrm{Li} * + n$	0.49	$^7\mathrm{Li} \to a + t$	1.19

Cross sections calculated in the framework of the optical model agree well with the experimental data in the forward hemisphere but the simple model fails to describe the rise of the cross section at large angles. Therefore, the CRC calculations were applied in order to reproduce this behavior at backward hemisphere. The contribution of the α-transfer mechanism does not affect the behavior of the cross sections in the main maximum of the angular distributions (up to 40°–60° angles) and the neutron pick-up dominates for angles up to 40°–50°. The cross section at angles of 120°–150° is fully reproduced by direct exchange mechanism with the transfer of α-particles in the ^{7}Li(d,^{6}Li)t reaction (Fig. 3 (right)) with reasonable values of the $^7\mathrm{Li} \to \alpha + t$ and $^6\mathrm{Li} \to \alpha + d$ spectroscopic factors.

4. Conclusion

Differential cross sections of scattered deuterons on ^{7}Li nuclei with excitation of the 0.478 MeV ($1/2^-$) state and tritons from the ^{7}Li(d,t)^{6}Li reaction with transition to the ground (1^+) state of the ^{6}Li nucleus have been measured at the deuteron beam with the energy of 14.5 MeV. The analysis of the experimental angular distributions was carried out via the CRC with taking into account the exchange of α-particle in the ^{7}Li(d,^{6}Li)t reaction. The calculations reproduce quite well the experimental cross sections in a wide angular range with the optical potentials found from the analysis of the elastic scattering. The deformation lengths for the ^{7}Li, ^{6}Li nuclei and spectroscopic factors for configurations $d + n$, $^6\mathrm{Li} + n$, $\alpha + d$, $\alpha + t$ are extracted. Obtained values are in good agreement with the previous work and with theoretical calculations within the framework of the translational invariant shell model.

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