Abstract

Angular distributions of differential cross sections have been analyzed for elastic, inelastic scattering and the (d,t) reaction on \(^7\)Li nuclei at 12, 15 and 18MeV deuterons energy. In framework of the present evaluation new phenomenological deuteron OMPs were developed for d+\(^7\)Li interactions from 8 to 28 MeV. For the reaction \(^7\)Li(d,t)\(^6\)Li, the new and early obtained data have been analyzed with Coupled Reaction Channel Method (CRC) taking into account alpha transfer mechanism, without excitations of core and cluster, and spectroscopic factor for \(\alpha+t\) configuration of \(^7\)Li was extracted. Parameters for real part of potential have been also calculated microscopically with double-folding model for d+\(^7\)Li and t+\(^6\)Li. The differential cross sections for the reaction \(^7\)Li(d,t)\(^6\)Li have been analyzed by DWBA and CRC methods. The effect of \(\alpha\) transfer on neutron transfer reaction \(^7\)Li(d,t)\(^6\)Li is discussed. Spectroscopic factors for \(n+t\) configuration of \(^7\)Li have been extracted from the experimental data.

Introduction

Recently, the development of fusion reactors attracts an interest in deuteron induced reactions, because the Li(d,xn) data up to 50 MeV is requested in the design of the International Fusion Materials Irradiation Facility (IFMIF) which is composed of an accelerator-driven deuteron-lithium neutron source for irradiation tests of fusion reactor
candidate materials [1]. Nuclear reactions of deuterons with light nuclei are used for the generation neutron beams. Experimental measurements for light nuclei are made for reaction cross sections \((d,n)\), \((d,p)\), \((d,t)\) and \((d,\alpha)\). Models used to describe nuclear reactions of deuterons with light nuclei are not straightforward due to the small number of nucleons which are modeling. Lithium nuclei have only a few nucleons and the deuterons are very loosely unbound system. These two reasons explain the difficulties faced applying nuclear models for the description the deuterons elastically scattered on \(^7\text{Li}\) [2]. In case of deuterons, there is no global optical model potential (OMP) which describe the scattering data over a wide range of energies and nuclei sufficiently well. This fact leads to an increased uncertainty in calculations of deuteron-induced reaction cross sections because the optical model is the basic ingredient of almost all nuclear model calculations. Moreover, the weak binding of the deuterons results in significant contributions of the breakup channel and enhances a variety of reactions at low bombarding energy. Nevertheless, a semi-microscopic analysis appears as an appropriate basis for the evaluation of the deuteron-nucleus optical potential. These potentials may be used for calculations of the deuteron-induced activation cross sections required for fusion applications [3]. The elastic scattering of deuterons on light nuclei has been less investigated mainly due to the difficulties to interpret it in terms of the usual optical-model potential (OMP) [4].

The nuclear potential is still ambiguous especially at small distances between interacting nuclei. From the phenomenological studies, it became clear that the main part of the nuclear interaction potential can be approximated by a Woods-Saxon form which gives a simple analytic expression, parameterized explicitly by the depth, the radius, and diffuseness of the potential well.

The optical model parameters (OMPs) are widely employed to generate the distorted waves used for analysis the cross section of different reactions, and these analyses have proved to be powerful tool to extract nuclear structure information. But the applicability of the optical model and Distorted Wave Born Approximation (DWBA) for light nuclei in its simple form is somewhat ambiguous because the number of target nucleons is small. Moreover, cluster effects might become important in the elastic scattering and reactions. Although the optical model and DWBA theory were not expected to work well for the nuclei with \(A=6\) and 7, the study of the transfer reactions on these light nuclei is attractive goal as other properties of these light systems have been calculated in details. The results of DWBA analysis of the transfer cross sections are typically highly sensitive to changing of the optical potential parameters. The calculated angular distribution of the nucleons transfer reaction can vary significantly even through the used OMPs fit well the elastic scattering in the entrance and exit reaction channels. The optical parameters used for analysis the elastic scattering should be fitted to be used in case of transfer reaction, which means that the change of the imaginary potential depth do not exceed 10-20% from optimal value used in elastic scattering analysis. Moreover, different optical potential parameterizations can provide spectroscopic factors (SFs) different up to factor 3 [5]. The choice of optical model parameters (OMPs) is very important because wrong estimation of OMPs used in elastic scattering would lead to wrong extracted SF.
An analysis of $^7\text{Li}(d,t)^6\text{Li}$ reaction

As one moves to larger angles, the DWBA is no longer expected to provide reasonable analysis. It should be mentioned that the SFs obtained from analysis depend strongly on the shape of the bound state potential commonly used in the Woods-Saxon form. It is known that by the interaction of the complex particles with light nuclei the specific effect called as an anomalous large-angle scattering (ALAS), which is impossible to interpret in the framework of the standard optical potential parameters are often observed. The nature of this phenomenon can be different, but in certain cases for $^6\text{Li}$ and $^7\text{Li}$ targets, having the pronounced $(\alpha+d)$ and $(\alpha+t)$ cluster structure and the differential cross sections increase at large angles. It is almost entirely connected with the transfer mechanism [6]. Both the $^7\text{Li}$ target nucleus and $^6\text{Li}$ residual nucleus are known to be well described by cluster model, and thus exchange effects are obvious in $^7\text{Li}(d,t)^6\text{Li}$ reaction. The reaction $^7\text{Li}(d,t)^6\text{Li}$ has been studied extensively but the studies were in forward angles only without the inclusion of exchange effect by A.R. Zander et al. [7], who have measured and analyzed the reaction $^7\text{Li}(d,t)^6\text{Li}$ at deuteron incident energy $E_d=12$ MeV. Their analysis was incomplete because they did not involve the exchange effects into their calculations. Also, there was no thing about the transfer reaction in the backward angles, alpha transfer. Several measurements were at forward angles only. Few attempts have been made to describe the exchange effects on $^7\text{Li}(d,t)^6\text{Li}$ reaction by F. Micheal et al. [8]. In the present work the CRC method is applied to the $^7\text{Li}(d,t)^6\text{Li}$ reaction to obtain the best analysis of experimental data using code FRESCO [9]. The spin-orbit effects are neglected in our analysis depending on the assumptions presented by F. Micheal [8]. Optical model ambiguities and their effect on calculations are investigated. SFs of both $^7\text{Li}=^6\text{Li}+n$ and $^6\text{Li}=\alpha+d$ are extracted from experimental data.

Phenomenological optical potential for deuterons elastic and inelastic scattering from $^7\text{Li}$

Data on elastic scattering are usually analyzed in the optical model (OM), in which the influence of inelastic channels is taken into account by introducing the complex potential with the imaginary term responsible for the partial absorption of the incoming flux. Usually, in the calculations of the complex potential depends only on the distance between centers-of-mass of colliding nuclei. In present work, the spin-orbit effect has been neglected. So, the optical potential can be written down in the form:

$$U(r) = V_C(r) - V(r) - i(W_v(r) + W_s(r))$$  \hspace{1cm} (1)

where, $V_C$ is Coulomb potential, $V(r)$ is real part, $W_V$ is imaginary volume part and $W_S$ is the imaginary surface part. Usually, the nuclear potential is taken Woods-Saxon with such set of phenomenological parameters that provides the best agreement with the experiment. The real part of this potential can be also calculated theoretically on the basis of fundamental nucleon-nucleon interaction by means of double folding technique. In framework of the present evaluation new phenomenological deuteron OMPs were developed for $d+^7\text{Li}$ interactions. The obtained OMPs are based on available experimental data for deuterons elastically scattered on $^7\text{Li}$. Table 1 contains Optical model potentials for deuterons elastic scattering on $^7\text{Li}$. The comparison of calculated
angular distributions for the deuterons elastic scattering on \(^7\)Li nuclei with experimental ones is shown in figure 1. The data were obtained earlier [10-18].

**Double folding analysis for \(t + ^7\)Li**

For exit channel \(^6\)Li+t, the microscopic potential calculated by us in the framework of the double folding model were used (see table 2). The real part is given in the following form:

\[
V_F(r) = \int dr_p \int dr \rho_p(r_p) \rho_t(r) v(r_p)
\]

where \(\rho_p\) is the projectile matter density distribution, \(\rho_t\) is the matter distribution of the target and \(r_p = r + r_t - r_p\).

**Table 1. Optical model potentials for deuterons elastic scattering on \(^7\)Li**

<table>
<thead>
<tr>
<th>(E_d) (MeV)</th>
<th>(V_R) (MeV)</th>
<th>(r_R) (fm)</th>
<th>(a_R) (fm)</th>
<th>(W_D) (MeV)</th>
<th>(r_D) (fm)</th>
<th>(a_D) (fm)</th>
<th>(V_{SO}) (MeV)</th>
<th>(r_{SO}) (fm)</th>
<th>(a_{SO}) (fm)</th>
<th>(r_C) (fm)</th>
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<tbody>
<tr>
<td>7</td>
<td>89.7</td>
<td>1.17</td>
<td>0.9</td>
<td>3.99</td>
<td>1.325</td>
<td>0.75</td>
<td>6.76</td>
<td>1.07</td>
<td>0.66</td>
<td>1.3</td>
</tr>
<tr>
<td>8</td>
<td>91.62</td>
<td>1.17</td>
<td>0.9</td>
<td>4.36</td>
<td>1.325</td>
<td>0.75</td>
<td>6.76</td>
<td>1.07</td>
<td>0.66</td>
<td>1.3</td>
</tr>
<tr>
<td>9</td>
<td>94.31</td>
<td>1.17</td>
<td>0.9</td>
<td>4.87</td>
<td>1.325</td>
<td>0.75</td>
<td>6.76</td>
<td>1.07</td>
<td>0.66</td>
<td>1.3</td>
</tr>
<tr>
<td>10</td>
<td>95.85</td>
<td>1.17</td>
<td>0.9</td>
<td>4.65</td>
<td>1.325</td>
<td>0.75</td>
<td>6.76</td>
<td>1.07</td>
<td>0.66</td>
<td>1.3</td>
</tr>
<tr>
<td>12</td>
<td>72.35</td>
<td>1.17</td>
<td>0.9</td>
<td>6.21</td>
<td>1.325</td>
<td>0.75</td>
<td>6.76</td>
<td>1.07</td>
<td>0.66</td>
<td>1.3</td>
</tr>
<tr>
<td>14.7</td>
<td>73.08</td>
<td>1.17</td>
<td>0.9</td>
<td>7.95</td>
<td>1.325</td>
<td>0.75</td>
<td>6.76</td>
<td>1.07</td>
<td>0.66</td>
<td>1.3</td>
</tr>
<tr>
<td>28</td>
<td>75.94</td>
<td>1.17</td>
<td>0.9</td>
<td>10.7</td>
<td>1.325</td>
<td>0.75</td>
<td>6.76</td>
<td>1.07</td>
<td>0.66</td>
<td>1.3</td>
</tr>
</tbody>
</table>

A popular choice for the effective NN-interaction has been one of the M3Y interactions. In the present calculation the effective NN-interaction is taken according to the form of

![Figure 1. Differential cross sections for elastic scattering of deuterons on \(^7\)Li nucleus at the energies indicated in the figure. The experimental data were obtained earlier [10-18].](image)
An analysis of $^{7}$Li(d,t)$^{6}$Li reaction

M3Y-interaction. The density distribution of triton was taken to be Gaussian form [19]:

$$\rho_p(r) = c \exp \left( -\alpha r^2 \right)$$

(7)

where $c = 0.20816$ fm$^{-3}$ and $\alpha = 0.53047$ fm$^{-2}$, these parameters correspond to a root-mean square (RMS) radius of triton of 1.68 fm. The nuclear density distribution of $^{6}$Li was taken according to [20]:

$$\rho_z = \frac{1}{8 \pi r^2} \left( \frac{1}{a z} \exp \left( -\frac{r^2}{4a z} \right) - \frac{c^2}{4b^2} \left( 6b^2 - r^2 \right) \exp \left( -\frac{r^2}{4b^2} \right) \right)$$

(8)

where $a$, $b$, and $c$ are constants: $a^2 = 0.87$ fm$^2$, $b^2 = 1.7$ fm$^2$ and $c^2 = 0.205$ fm$^2$. The real potential $V_F(r)$ is obtained by integrating an effective nucleon-nucleon interaction over the density distributions of the two colliding nuclei. The real folded potential $V_F(r)$ was calculated using DFPOT [21] and was approximated by the Woods-Saxon function with parameters which are given in Table 2. The imaginary part of potential was normalized and the normalization factor was taken to be 0.79. It is difficult to make reliable analysis if you have not global optical potential parameters for both entrance and exit channel. Both discrete and continuous ambiguities arise in the optical model analyses. Elastic scattering of deuterons on $^{6,7}$Li in wide range of energy has been studied in details in [22, 2]. H. Ludecke et al. [23] had their OMPs which have a very poor analysis in CRC method.

The reaction $^{7}$Li(d,t)$^{6}$Li analysis

The analysis of the reaction $^{7}$Li(d,t)$^{6}$Li has been performed using coupled reaction channel (CRC) method. The entrance channel OMPs were taken from the analysis made by [6,8], where the exit channel it was taken from [23,24]. RC was taken equal 1.25 fm. The spectroscopic factor of $^{6}$Li$\equiv\alpha+d$ was taken from literature and it was in good agreement with theoretical values [25].

The $\alpha+d$ and $^4$He+t cluster wave functions for the 2s ground state (1$^+$) and the 1d excited state (3$^+$) of the $^{6}$Li nucleus were used. The calculations for the $^{7}$Li nucleus in $^{6}$Li+n configuration were performed with the 2p and 1p bound state wave functions respectively. These functions were computed with Woods-Saxon potential having standard geometry parameters $r_0 = 1.25$ fm and $a = 0.65$ fm. Its depth is determined from the cluster binding energies. In case of the $^{6}$Li nucleus in $\alpha+d$ configuration and $^{7}$Li nucleus in $\alpha+t$ configuration, the calculations were computed with Woods-Saxon potential having geometry parameters $r_0=0.95(A_1^{1/3}+A_2^{1/3})$ [26].

As it is seen from the Figures (3-5) the calculated cross sections in general reproduce the experimental data rather well. The best fit at 18 MeV was obtained using OMPs A$_1$+B$_1$ (see Table 2). When OMPs A$_4$+B$_3$ at $E_d=15$ MeV was used the fit of the experimental data somewhat worse. But in case of using A$_2$+B$_2$ taking into account the cluster exchange mechanism by CRC method (solid curves) provides an explanation for the considerable increase of the cross section in the backward angles at the deuteron energies of 12, 15 and 18 MeV. The CRC cross sections differ from DWBA (dashed curves) only at the angles more than 70° where at the smaller angles there is an equivalent description of experimental data. Optical model parameters sets used into analysis are shown in Table 2. The spectroscopic amplitudes (SA) for the $\alpha+d$ and $\alpha+t$ configurations of the ground and excited states of the $^{6}$Li and $^{7}$Li nuclei were extracted and compared.
with these values taken from [25]. But their signs have been changed according to the FRESKO code convention:

$$S_{FRESKO} = (-1)^{J_c+J_A-J_x} S_x,$$

(9)

where $J_c$, $J_A$ and $j_x$ are spins of the core, composite and transferred nuclei respectively.

The value of the spectroscopic amplitude for the $t^6Li+d+n$ configuration was $SA = 1.2247$ if the standard geometry of the Woods-Saxon potential is used. The spectroscopic amplitudes were extracted for the ground and first excited states of $^7Li^6Li+n$ configuration. Therefore in our analysis of experimental data without polarization information we can extract only summed SF ($S_{3/2}+S_{1/2}$). The extraction of spectroscopic factors in all calculations with FRESKO code was made by varying both initial values $S_{3/2}$ and $S_{1/2}$ by the same factor to normalize the calculated differential cross sections to the experimental ones in the region of the main maximum of angular distribution. The average obtained values of SFs ($SF=(SA)^2$) under all used OMP sets are compared with shell-model calculations and other experimental values in the table 3.
An analysis of $^7\text{Li}(d,t)^6\text{Li}$ reaction

Figure 2. The Angular distributions for deuterons from the reaction $^7\text{Li}(d,t)^6\text{Li}$ at the deuterons energies of 12, 15, and 18 MeV (see left panel). Experimental data are square dots, solid curves are differential cross sections calculated with all couplings. DWBA calculations represented as solid lines at 15 and 18 MeV. Solid curves at 12 MeV (right panel) are differential cross sections calculated with CRC where dash and dot lines are DF and DWBA calculations respectively at 12 MeV. At 12 MeV, OMPs were used in calculations are $A_2+B_2$, $A_3+B_3$ and $A_2+B_5$. Experimental data (square dots) were taken from [7].

Table 3 spectroscopic amplitudes for the $^7\text{Li}(d,t)^6\text{Li}$ reaction. Values in parentheses correspond to SA ($t = d+n$) = 1.224.

<table>
<thead>
<tr>
<th>system</th>
<th>Extracted values using CRC method</th>
<th>Extracted values using DWBA method</th>
<th>Theoretical values</th>
<th>references</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^7\text{Li} \equiv ^6\text{Li}+n$</td>
<td>(1P$_{3/2}$) -0.837</td>
<td>(1P$_{1/2}$) -0.72</td>
<td>(1P$_{1/2}$) -0.6573</td>
<td>[25]</td>
</tr>
<tr>
<td></td>
<td>(1P$_{3/2}$) +0.850</td>
<td>(1P$_{3/2}$) +0.78</td>
<td>(1P$_{3/2}$) +0.7349</td>
<td>[25]</td>
</tr>
<tr>
<td>$^7\text{Li} \equiv ^4\text{He}+t$</td>
<td>(2P$_{3/2}$) +1.180 (fixed)</td>
<td>(2P$_{3/2}$) +1.0913</td>
<td>(2S$_1$) +1.0610</td>
<td>[25]</td>
</tr>
<tr>
<td>$^6\text{Li} \equiv ^4\text{He}+d$</td>
<td>(2S$_1$) +1.180 (fixed)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4 bound state parameters used in the calculations of the reaction $^7\text{Li}(d,t)^6\text{Li}$

<table>
<thead>
<tr>
<th>system</th>
<th>$E_B$ (MeV)</th>
<th>$r$ (fm)</th>
<th>$a$ (fm)</th>
<th>references</th>
</tr>
</thead>
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<tr>
<td>d+n</td>
<td>6.257</td>
<td>1.25</td>
<td>0.65</td>
<td></td>
</tr>
<tr>
<td>$^7\text{Li}+n$</td>
<td>7.250</td>
<td>1.25</td>
<td>0.65</td>
<td></td>
</tr>
<tr>
<td>$^4\text{He}+t$</td>
<td>2.467</td>
<td>0.95($A_1^{1/2} + A_2^{1/2}$)</td>
<td>0.65</td>
<td>[26]</td>
</tr>
<tr>
<td>$^4\text{He}+d$</td>
<td>1.474</td>
<td>0.95($A_1^{1/2} + A_2^{1/2}$)</td>
<td>0.65</td>
<td>[26]</td>
</tr>
</tbody>
</table>

Conclusion

An analysis of deuterons elastically scattered by $^7\text{Li}$ nuclei in wide energy range has been performed using optical model. New sets of OMPs have been obtained in this study. Available data from literature have been analyzed with the optical model, DWBA approach and coupled reaction channels (CRC) method. The microscopic potential of deuterons elastically scattered by $^7\text{Li}$ was calculated in the framework of the double folding model with normalization factor $N = 0.79$. Using the OMPs found from the analysis of the elastic scattering of deuterons on $^7\text{Li}$ nuclei, coupled reaction channels.
method (CRC) could theoretically describe the experimental differential cross-sections of the reaction \(^7\text{Li}(d,t)^6\text{Li}\) and \(^7\text{Li}(d,^6\text{Li})\) reaction, where the dominant mechanism is alpha-cluster transfer. In analysis of the \((d,t)\) reaction, the role of the \(n\)- and \(\alpha\)-clusters one-step transfer mechanisms have been evaluated. The effect of CRC appears obvious in all cases. Spectroscopic factors of \(^7\text{Li} \equiv ^6\text{Li} + n\) configuration have been extracted and agree with theoretical values obtained in [25].

References


12. V.I. Chuev, V.V. Davdov et al., Journal de Physique 32, Colloque C6, 163 (1971).

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