THE CHANNEL COUPLING AND TRITON CLUSTER EXCHANGE EFFECTS IN ^{3}He SCATTERING ON ^{6}Li NUCLEI

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(Received March 20, 2014; revised version received July 2, 2014)

Existing experimental data on elastic and inelastic scattering of ^{3}He projectiles on the ^{6}Li nuclei in the energy range from 18 to 217 MeV were analyzed within the framework of the coupled reaction channels. The coupling of the elastic and inelastic scattering with the transition to the excited state of 2.186 MeV (3^{+}) and triton-exchange mechanism were taken into account in calculations. Phenomenological potentials with depths depending on the energy at fixed values of the geometric parameters were found. These potentials describe well the experimental angular distributions for the elastic scattering. However, there is a significant underestimation of the cross sections for the inelastic scattering at middle angles. Energy dependence of the volume integrals of the real potential for ^{3}He + ^{6}Li system is consistent with similar data for other systems p + ^{6}Li, d + ^{6}Li, α + ^{6}Li, ^{12}C + ^{12}C and also with the predictions of the microscopic theory.

DOI:10.5506/APhysPolB.45.1853
PACS numbers: 24.50.+g, 24.10.Eq, 25.45.Hi

1. Introduction

The cluster aspects play a very important role in interaction of particles with light nuclei ($A \leq 16$). From this point of view, a typical example is the nucleus ^{6}Li, whose ground state, according to the theory [1], is defined by two overlapping configurations $\alpha + d$ and $^3\mathrm{He} + t$.

This structure affects not only the nuclear reaction cross sections, but also cross sections of the elastic scattering of deuterons, tritons, ^{3}He and α-particles due to contribution of the exchange mechanisms with clusters transfer $^6\mathrm{Li}(x,{}^6\mathrm{Li})x$, where $x = d, t$, ^{3}He, α. In the experiment, these mechanisms are not distinguishable from potential scattering.

Contribution of exchange mechanism is particularly high at large scattering angles, where an anomalous increase in the cross sections, which is not explained by optical model with reasonable values of the potential parameters, is observed. Well-defined cluster structure is the main cause of failed attempts to include light nuclei in a global description of scattering of deuterons [2, 3], ^{3}He [3, 4] and α-particles [6, 7] on the basis of the optical model. Another evident reason is that the behavior of cross sections at medium and large angles, besides transfer of clusters, strongly depends on effects of coupled channels of the elastic and inelastic scattering. Indeed, due to the deformation caused by the isolation of the clusters, the probability of the electric quadrupole transition from the ground state of ^{6}Li ($J^\pi = 1^+$) to the first excited state ($E_x = 2.186$ MeV, $J^\pi = 3^+$) is quite high. It is more than one order higher than the probability of single-particle transition [8, 9]. Thus, neglecting of coupled channels can lead to unphysical values of potential parameters derived from the analysis of experimental data.

Not so much work was devoted to experimental study of the scattering of ^{3}He ions on ^{6}Li nuclei. The elastic scattering angular distributions were previously measured at angles up to 120° in the center of mass at nine energies from 8 to 20 MeV [10]. There are data obtained at higher energies of ^{3}He: 24.6 and 27 MeV [11], 44.04 MeV [12] 34, 50, 60, 72 MeV [13, 14], and 217 MeV [15]. In the full angular range, the data were measured only for the energies 34, 44, 50 and 72 MeV [12–14]. As was shown in the analysis, the standard optical model gives an acceptable description of the experimental data in the forward hemisphere only. Inclusion of the triton cluster elastic transfer mechanism allows reproducing the qualitative features of the behavior of the differential cross sections at large angles [14, 16, 17]. However, even taking into account the elastic transfer, describing the experimental cross sections at intermediate angles, *e.g.* where the cross section of potential scattering and transfer mechanism are comparable, is impossible. Moreover, the experimental spectroscopic factor for the configuration of $^3\mathrm{He} + t$ is energy dependent and varies smoothly from the value of 0.1 at

$E(^3\mathrm{He}) = 34$ MeV to 0.45 at $E(^3\mathrm{He}) = 72$ MeV [14]. Perhaps this is due to the incorrect choice of the depth of the imaginary potential, as follows from the analysis performed in [16, 17].

It should be noted, that the accounting of cluster exchange mechanism and a more accurate selection of the imaginary part of the potential only do not remove the problem of poor description of the experimental data at intermediate angles. Obviously, besides the elastic transfer mechanism of triton in the scattering of ^{3}He ions on ^{6}Li nuclei, the effect of coupled channels is required to consider in the analysis. The necessity of such approach has been recently demonstrated in the analysis of the scattering of α-particles [18] and deuteron [19] on the same nucleus.

The aim of this work is to obtain an unified description of existing data on the scattering of ^{3}He ions on ^{6}Li nuclei with accounting the coupling channels including the mechanism of triton cluster exchange.

2. Analysis and discussion

The analysis of selected experimental data of the scattering of ^{3}He ions on ^{6}Li nuclei, measured in the full range of angles at energies of 34, 44.04, 50, 60 and 72 MeV [12–14, 17], and in the angular range of the forward hemisphere at $E(^3\mathrm{He}) = 18$, 24.6 and 217 MeV [11, 15] is presented in this work. The calculations in the framework of the coupled reaction channels method, using the program FRESCO [20] were done. The coupling scheme included both elastic and inelastic scattering with excitation of the 3^+ level of the ^{6}Li ($E_x = 2.186$ MeV) nucleus and triton transfer reaction ^{6}Li(^{3}He, ^{6}Li)^{3}He (see Fig. 1). Transitions $1^+ \leftrightarrow 3^+$ were calculated using the rotational model with the form factor for quadrupole deformation ($\lambda = 2$)

$$V_\lambda(r) = \frac{\delta_\lambda}{\sqrt{4\pi}} \frac{dU(r)}{dr}\,,$$

where $U(r)$ — deformed potential of nucleus–nucleus interaction, δ_λ — multipole deformation length. This analysis also included the effects of reorientation ($1^+ \leftrightarrow 1^+$, $3^+ \leftrightarrow 3^+$) defined by the matrix element $\langle EJ \mid V_\lambda \mid EJ\rangle$.

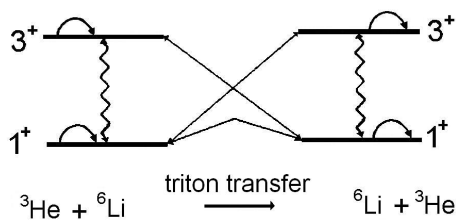

Fig. 1. The coupling scheme used in the coupled reaction channels calculations of ^{3}He scattering by ^{6}Li nuclei.

As can be seen from Fig. 1, we took into account only two partitions of the nine-nucleon system: ^{3}He + ^{6}Li and ^{6}Li + ^{3}He coupled by triton transfer reaction.

For calculations of distortion in the input and output channels, the nuclear central potential with volume absorption and spin–orbit term were used. The radial dependences were described by the Saxon–Woods form factors

$$f(r) = \left[1 + \exp\left(\frac{r - r_0 A^{1/3}}{a}\right)\right]^{-1},$$

where A — mass number of nucleus, r_0 and a — reduced radius and diffuseness, suitable for a variety of potential components.

For searching the optimal parameters, giving the best description of the experimental data, the starting potentials obtained from the analysis of the elastic scattering of ^{3}He ions on ^{6}Li nuclei in the forward hemisphere were taken from [14]. Then, in order to reduce the ambiguities in search, all geometric parameters (radius, diffuseness) and the depth of the spin–orbit potential were fixed at values: $r_V = 1.15$ fm, $a_V = 0.65$ fm, $r_W = 1.46$ fm, $a_W = 0.85$ fm, $V_{\rm SO} = 4$ MeV, $r_{\rm SO} = 1.15$ fm, $a_{\rm SO} = 0.8$ fm, $r_{\rm C} = 1.3$ fm, where $r_{\rm C}$ defines the radius $R_{\rm C} = r_{\rm C} A_t^{1/3}$ of the Coulomb potential of a uniformly charged sphere. Only the depths of the central potential (V, W) were varied to obtain the best description of the experimental angular distributions. Selected geometric parameters are close to the values obtained in the global description of the elastic scattering of ^{3}He ions on nuclei in the region $A = 10$–208 in the energy range of 10–210 MeV [4]. The obtained potentials and values of the volume integrals, normalized to a pair of interacting particles are shown in Table I.

As is seen from Table I and Fig. 2, the depth of the real part of the potential (V) and the corresponding value of the volume integral $(J_{\rm V})$ smoothly decreased with energy increasing and is well described by the relation $V = 116.2\exp(-E/45.9) + 63$. In the energy range from 18 to 72 MeV, this dependence can be approximated by a linear function of $V = 156.7$–$1.04\ E$. In contrast, the imaginary part (W), described by the function $W = 0.15$ $\exp(E/39.6) + 29.5$, did not significantly change in the energy range of 34–72 MeV. This is in agreement with the behavior of the global potential found in [4].

The comparison of calculated cross sections for elastic and inelastic scattering with the experimental data measured at different energies is shown in Figs. 3 and 4. Differential cross sections for the triton cluster exchange mechanism were calculated using the Finite Range DWBA incorporated in FRESCO. $2S$- and $1D$-cluster (^{3}He + t) wave functions for the ground state (1^+) and the excited (3^+) states of the ^{6}Li nuclei were calculated in a stan-

TABLE I

The potential parameters obtained from the coupled reaction channels analysis of scattering of ^{3}He ions on ^{6}Li nuclei.

$E(^3\text{He})$ [MeV]	$-V$ [MeV]	J_V [MeV fm^3]	$-W$ [MeV]	J_W [MeV fm^3]
18	140	583	35	307
24.6	130	541	25	220
34	121	504	30	264
44.04	110	458	25	220
50	105	437	37	325
60	90	375	30	264
72	85	354	28	246
217	64	271	65	571

The remaining parameters are fixed at values: $r_V = 1.15$ fm, $a_V = 0.65$ fm, $r_W = 1.46$ fm, $a_W = 0.85$ fm, $V_{\text{SO}} = 4$ MeV, $r_{\text{SO}} = 1.15$ fm, $a_{\text{SO}} = 0.8$ fm, $r_{\text{C}} = 1.3$ fm.

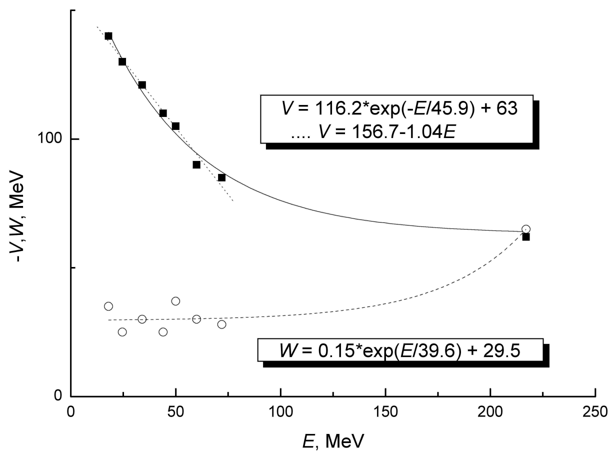

Fig. 2. The energy dependence of the real (■) and imaginary (○) depths of potentials found.

dard way, adjusting the depth of the real Saxon–Woods potential to obtain the experimental binding energy of clusters. The geometric parameters of the potential were fixed at values of the radius $R = 2.4$ fm and diffuseness $a = 0.65$ fm. To achieve the best agreement with experiment, quadrupole deformation length δ_2 was varied from 3.0 to 3.5 fm. Spectroscopic factor for the configuration of ^{3}He $+ t$ was assumed to be $S = 0.89$, for both ground and excited states of ^{6}Li, according to [21].

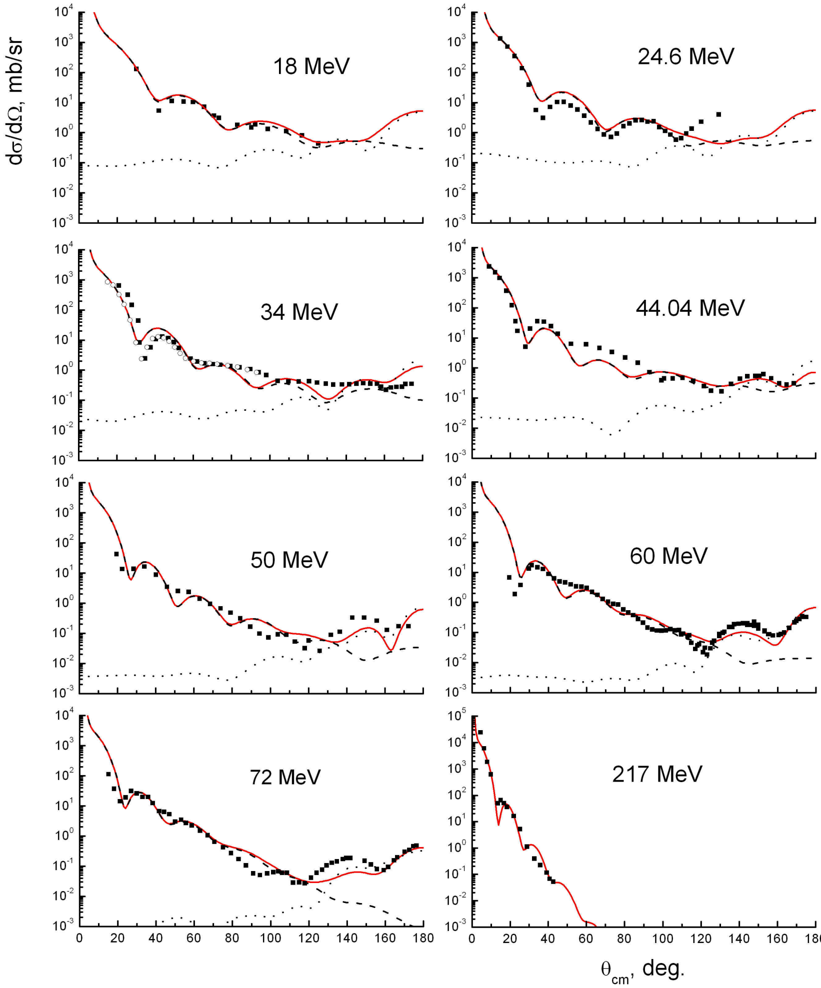

Fig. 3. The angular distributions of ^{3}He ions elastically scattered on ^{6}Li nuclei at 34, 50, 60 and 72 MeV energies. Open circles are experimental data obtained in the present work, square points are data taken from [11–15, 17, 24]. Curves are the results of calculations by the coupled reaction channels method. Solid curves are calculations with taking into account all couplings at the coherent addition of scattering and triton transfer mechanisms. Dashed curves are calculations with the coupling of the elastic and inelastic scattering only. Dotted curves are calculations for the triton exchange mechanism.

As one can see from Fig. 3, the calculated angular distributions for elastic scattering, taking into account all the couplings (solid lines) are in good agreement with the experiment. Theoretical cross sections calculated using

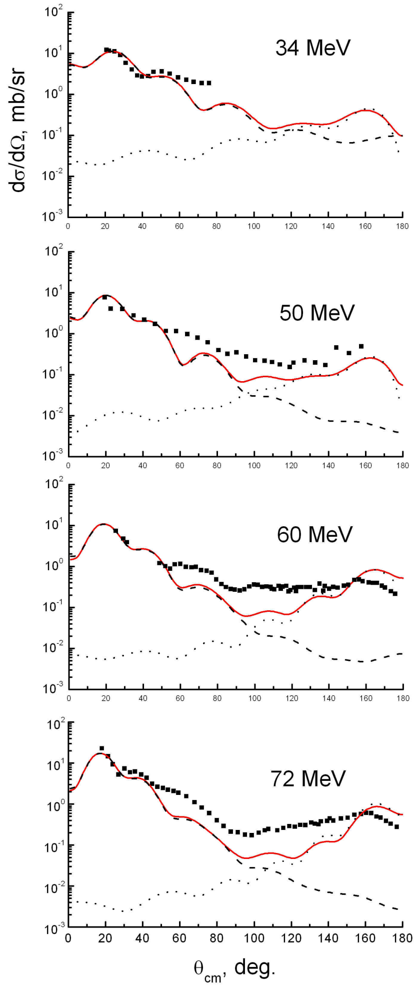

Fig. 4. The angular distributions of the ^{3}He ions scattered on ^{6}Li nuclei at 34, 50, 60 and 72 MeV energies with excitation of the 2.186 MeV (3^+) state. All notations are the same as in Fig. 3.

the optical model potentials found in [14], cannot explain the rise of the cross sections at large angles. It is also impossible to reach agreement with the experiment, taking into account only the connection of the elastic and inelastic scattering (see dashed lines in Fig. 3). The behavior of cross sections at large angles can be explained including the triton transfer mechanism (dotted curves) only.

The calculated cross sections for inelastic scattering (see Fig. 4), obtained with inclusion of coupling with elastic scattering and inelastic triton transfer mechanism, show quite well the general nature of experimental angular distributions with weak diffraction structure, measured at energies of 34, 50, 60 and 72 MeV [17, 24] (solid curves). However, there is a significant underestimation of the experimental cross sections in the middle angles region.

Taking into account the mean square Coulomb radius of the ^{6}Li nucleus (2.51 fm), known from the electron scattering data [8], and the effective charge radius $R_{\mathrm{C}} = 3.24$ fm, calculated by formula [25],

$$R = \sqrt{5/3}\left\langle r^2\right\rangle^{1/2} ,$$

the averaged value of the deformation length ($\delta_2 = 3.25$ fm) found in our analysis corresponds to the reduced electric quadrupole transition probability B(E2) $= 22.8 \pm 3$ e^{2}fm^4. The resulting value can be compared with the B(E2) value (25.6 ± 2 e^{2}fm^4) known from the inelastic scattering of electrons [8]. It should be noted, however, that the rotational model cannot be applied to such few-nucleon system as ^{6}Li because its form is almost spherical. Quadrupole moment of ^{6}Li makes only $Q = 0.818$ mb [8]. Nevertheless, the probability of electric quadrupole transition is much higher than the single-particle value and it is due not to an ordinary quadrupole deformation but the dumbbell shape of the nucleus arising from separation of clusters. That is why the inclusion to the coupling scheme of 3^+ state gives a fair description of elastic scattering. The inadequacy of the simple rotational model applied to the ^{6}Li nucleus is only one of the possible reasons for the poor description of inelastic scattering at intermediate angles. Another reason is that this nucleus is a loosely bound system, and the 2.186 MeV (3^+) state is unstable with respect to decay $^6\mathrm{Li} \to \alpha + d$. Therefore, this nucleus decays with high probability to three-particles system in the final state with formation of a continuous spectrum. In this case, the coupling with the continuum can be quite substantial.

Theoretical values of the spectroscopic factors for tritons in different approaches are within 0.5–0.9 interval [21–23], which is consistent with the result of this work. It should be stressed that in our analysis the triton spectroscopic factors for both ground and excited states were fixed at $S = 0.89$ according to the theoretical predictions and did not depend on the energy, in contrast to the results obtained in [14, 17] where, as it was also pointed out in the introduction, this value is energy dependent and varies smoothly from 0.1 at $E(^3\mathrm{He}) = 34$ MeV to 0.45 at $E(^3\mathrm{He}) = 72$ MeV.

It is interesting to compare the values of the volume integrals of the real part of the potentials in Table I with similar values obtained for other colliding systems. Such a comparison is shown in Fig. 5, which shows the value of J_V, normalized to a pair of interacting particles for systems ^{3}He + ^{6}Li (this work), d + ^{6}Li [19] and α + ^{6}Li [18] dependent on the energy per nucleon (E/A) of the incident projectiles. The approximation of J_V for p + ^{6}Li [26] (dotted line), ^{12}C + ^{12}C [27] (dashed curve) and ^{3}He + ^{6}Li [4] (solid curve) systems is also shown. As can be seen from Fig. 5, the energy dependence of the volume integrals for these systems is similar and is characterized by a smooth decrease with increasing energy. However, there is a tendency to decrease J_V with increasing masses of the colliding nuclei, according to the microscopic theory and can be associated with dependence of the effective nucleon–nucleon interaction with the nuclear density. This effect was also observed earlier in the energy dependences of the J_V for the systems p + ^{12}C, α + ^{16}O, ^{12}C + ^{12}C [27].

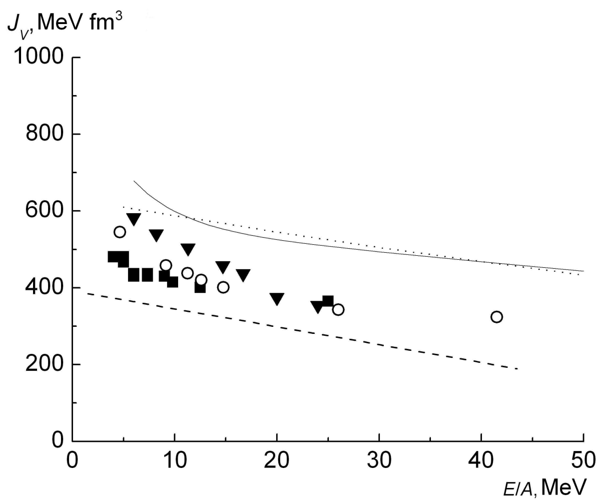

Fig. 5. The energy per nucleon (E/A) dependence of the volume integrals of the real potentials (J_V), found from the analysis of the scattering for ^{3}He + ^{6}Li (this work (▼)), d + ^{6}Li [19] (■) and α + ^{6}Li [18] (○) systems. Curves are approximations of the energy dependence of J_V for p + ^{6}Li [26] (dotted), ^{3}He + ^{6}Li [4] (solid), and ^{12}C + ^{12}C [27] (dashed) systems.

3. Summary and conclusions

The existing experimental data on elastic and inelastic scattering of ^{3}He ions on ^{6}Li nuclei in the energy range of 18–217 MeV were analyzed using the coupled reaction channels method with triton cluster exchange mechanism. The phenomenological potentials with depths dependent on energy at fixed values of the geometric parameters were found. These potentials describe well the experimental angular distributions of elastic scattering at all energies in the full angular range. However, there is a significant underestimation of experimental cross sections for the inelastic scattering at the middle angles region. The reasons may be an inadequacy of the simple rotational model for the ^{6}Li nucleus, and coupling effects with the continuum.

Our analysis showed that the depth of the real part of potential (V) and corresponding value of the volume integral (J_{V}) smoothly decrease with energy increasing. The behavior of volume integral for ^{3}He + ^{6}Li is consistent with similar data for other systems p + ^{6}Li, d + ^{6}Li, α + ^{6}Li, ^{12}C + ^{12}C and also with predictions of the microscopic theory.

In addition, the extracted values of triton spectroscopic factors for both ground and excited states do not depend on energy, in contrast to the results obtained in [14, 17], and are consistent with theoretical values.

A good description of all data on elastic scattering of ^{3}He ions on ^{6}Li nuclei with physically reasonable values of the parameters of the optical potentials, cluster spectroscopic factors and the deformation length was obtained. This suggests that the basic processes having influence on character of the ^{3}He scattering were accounted and contribution of other more complex mechanisms, in particular the two-step processes are small.

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