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Application of the Continuum Discretized Coupled Channels Method to Nucleon-induced Reactions on ^{6,7}Li for Energies up to 150 MeV

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Nucleon-induced reactions on ^{6,7}Li are analyzed systematically over a wide range of incident energies up to 150 MeV by using three-body continuum discretized coupled channels method (CDCC) capable of treating the breakup of ^{6,7}Li. The diagonal and coupling potentials in the CDCC equation are obtained by folding the complex Jeukenne-Lejeune-Mahaux effective nucleon-nucleon interaction with transition densities. The normalization factors of the complex effective interaction are determined so as to reproduce experimental data on neutron total and proton reaction cross sections. Triton emission from ^{7}Li breakup channel and $p(n)+{}^7\text{Li}\rightarrow t+{}^5\text{Li}^*({}^5\text{He}^*)$ channel is analyzed by the sequential decay model and final state interaction model, respectively. In most cases, the calculated results are in good agreement with experimental data except for the nucleon production double differential cross sections (DDX) at relatively low emission energies.

I. INTRODUCTION

In fusion technology, lithium is an important element relevant to not only a tritium breeding material in D-T fusion reactors but also a candidate for target material in the intense neutron source of International Fusion Materials Irradiation Facility [1]. Accurate nuclear data are therefore required for nucleon induced reactions on ^{6,7}Li for incident energies up to 150 MeV [2]. Since ^{6}Li and ^{7}Li can easily break up, namely, $^6\text{Li}\rightarrow d+\alpha$ and $^7\text{Li}\rightarrow t+\alpha$, systematic understanding of the breakup reaction mechanism is also an interesting and meaningful subject from the viewpoint of nuclear physics. Therefore, the study of nucleon induced reactions on ^{6,7}Li is not only of application value but also of theoretical significance.

II. THEORETICAL MODEL

Neutron total cross sections, proton reaction cross sections, nucleon scattering spectra and breakup cross sections for ^{6,7}Li are analyzed with the three-body continuum discretized coupled channels method (CDCC) [3–6]. In CDCC, ^{6}Li and ^{7}Li are considered as a $d+\alpha$ and a $t+\alpha$ cluster, respectively. The breakup continuum states of ^{6,7}Li are truncated and discretized to finite number of discrete states by the pseudostate method [6, 7] with the internal interactions as Gaussian forms, sequentially the breakup effect is analyzed by coupled channel method considering the discretized states. The diagonal and coupling potentials between nucleon and ^{6,7}Li are obtained by folding complex Jeukenne-Lejeune-Mahaux (JLM) effective nucleon-nucleon interaction with the transition densities between the corresponding bound and discretized states. The normalization factors of JLM interaction are determined so as to reproduce the experimental data of neutron total and proton reaction cross sections. The detailed description of the formulation of CDCC and normalization factors of JLM nucleon-nucleon interaction used is given in Ref. [8].

The triton production DDX from the breakup of ^{7}Li* excited by nucleon inelastic scattering from ^{7}Li is calculated with the sequential decay (SD) model [9]. The formulation is expressed as

$$\left(\frac{d^2\sigma}{dE_t d\Omega_t}\right)^{J^\pi}_{seq} = \sum_i \frac{\sigma_i^{J^\pi}}{2\pi}\int L_1(E_N \rightarrow E^i_{Li^*}) \cdot L_2(E^i_{Li^*} \rightarrow E_t)\Lambda(\mu_{Nt})dE^i_{Li^*}, \tag{1}$$

where $\sigma_i^{J^\pi}$ is the breakup cross section from the ith discretized state of ^{7}Li* which is obtained with CDCC. L_1 denotes the probability that an incident nucleon with energy E_N produces a recoil nucleus ^{7}Li* with energy $E^i_{Li^*}$. L_2 denotes the probability that an intermediate ^{7}Li* with energy $E^i_{Li^*}$ produces a triton with energy E_t. The triton emission is assumed to be isotropic, then L_1 and L_2 can be obtained using the conservation of momentum and en-

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ergy [9]. $\Lambda(\mu_{Nt})$ stands for the probability of the cosine of the angle between the direction of incident nucleon and emitted triton being μ_{Nt}.

The incident energies of the existing experimental data of triton production DDX are below 20 MeV where there are other reaction processes, $p(n)+^7\text{Li}\to t+^5\text{Li}^*(^5\text{He}^*)$, contributing to triton emission. In order to compare the calculated results with experimental data, triton emission from these reaction processes is also calculated by the final state interaction (FSI) model [10]. Here, ^{5}Li* and ^{5}He* are considered as α-p and α-n systems, respectively. The formulation is expressed as

$$\begin{aligned}&\left(\frac{d^2\sigma}{dE_t d\Omega_t}\right)_{FSI} \\ &= N_F \sin^2\beta_l \frac{F_l^2(k_{N\alpha}a)+G_l^2(k_{N\alpha}a)}{(k_{N\alpha}a)^2}\rho(E_t^{lab}),\end{aligned} \tag{2}$$

where N_F is a normalization parameter which is determined by fitting to experimental data, F_l and G_l are the first-order spherical Bessel functions for the α-n system and the Coulomb wave functions for the α-p system, k denotes the wave number of $p(n)$ in α-$p(n)$ system, a is the channel radius, $\rho(E_t^{lab})$ is the phase space factor for triton emission energy E_t^{lab}, and β_l denotes the α-$p(n)$ phase shift. The proton and neutron emission from sequential decay of ^{5}Li* and ^{5}He* produced in these reaction processes, namely, $^5\text{Li}^*\to p+\alpha$ and $^5\text{He}^*\to n+\alpha$, are also calculated with the above-mentioned SD model.

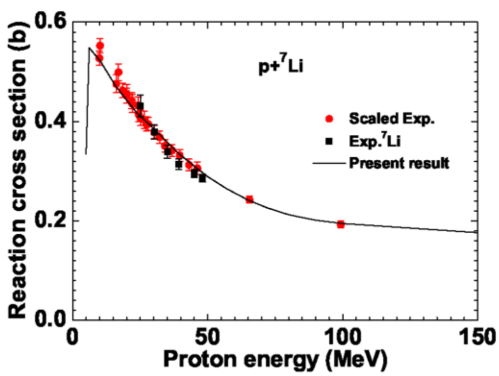

FIG. 1. Comparison of the calculated result (solid line) of reaction cross section for $p+^7$Li reaction with experimental data [11–15]. The solid squares and circles denote the experimental data for $p+^7$Li reaction and the scaled experimental data transformed from $p+^9$Be reaction, respectively.

III. RESULTS AND DISCUSSION

Neutron total cross sections, proton reaction cross sections and nucleon elastic and inelastic scattering differential cross sections are calculated with CDCC and reported in Ref. [8]. In most cases, they are in good agreement

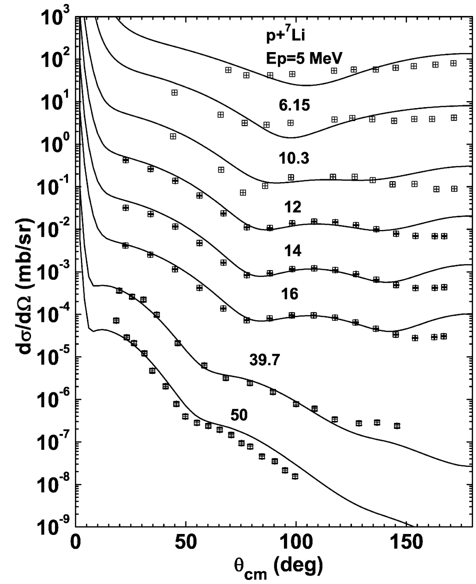

FIG. 2. Comparison of the calculated angular distributions (solid lines) of proton elastic scattering from ^{7}Li with experimental data [16–18]. The data are shifted downward by factors of 10^0, 10^{-1}, 10^{-2}, and so on.

with experimental data. Figs. 1 and 2 show comparisons of calculated results and experimental data [11–18] of the reaction cross section and elastic scattering differential cross section for $p+^7$Li reaction, respectively. Since the measured proton reaction cross sections for ^{7}Li [11] are not sufficient enough, we scale the experimental data [12–15] from $p+^9$Be reaction as supplement, which are shown by the solid circles in Fig. 1. The scaling method is described in Ref. [8]. Generally good agreement with the experimental data is obtained for both of the calculated results.

The proton(neutron) production DDXs for $p(n)+^6$Li reactions are also calculated with CDCC. The calculated results reproduce experimental data well except for relatively low emission energies. Fig. 3 shows the calculated result of neutron production DDX for $n+^6$Li reaction at an incident energy of 14.1 MeV compared with experimental data [19]. The contributions corresponding to unbound ^{1}S, ^{1}D, ^{2}D and ^{3}D states of ^{6}Li are denoted by dash-dot-dotted, dashed, short dashed and dash-dotted lines, respectively. Three peaks of the calculated results represent the elastic, inelastic to the 3^+ resonance and 2^+ resonance components, respectively, from high emission energy end. The calculated result is in good agreement with the experimental data at relatively high emission energies, while it underestimates the experimental data in the low emission energy region corresponding to highly exited states of ^{6}Li. The reason for the discrepancy is that some other reaction channels, e.g., four-body breakup channel $^6\text{Li}(n,nnp)\alpha$ [6], contribute to this energy region, which cannot be calculated with the present three-body CDCC.