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Analysis of deuteron breakup reactions for energies up to 100 MeV

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Abstract. Inclusive nucleon spectra from deuteron breakup reactions on ^{7}Li and ^{12}C up to 100 MeV are analyzed by using the continuum discretized coupled channels theory for elastic breakup process and the Glauber model for nucleon stripping process. The preequilibrium and evaporation components are estimated phenomenologically in terms of the moving source model. The calculation reproduces a prominent bump observed around half the incident energy in experimental inclusive spectra at forward angles quite well. The present analysis clarifies that the stripping process is more dominant than the elastic breakup process in deuteron breakup reactions on ^{7}Li and ^{12}C.

1 Introduction

Deuteron breakup reactions have attracted considerable attention in the study of projectile breakup of exotic and halo nuclei as well as in applications associated with accelerator driven neutron sources. For instance, the Li(d, xn) reaction is regarded as one of the most promising reactions to produce intense neutron beams at the International Fusion Material Irradiation Facility (IFMIF) [1]. Therefore, understanding of the nuclear interaction of deuterons with materials is highly required for estimating neutron yields and induced radioactivities in the engineering design of such neutron sources and accelerator shielding.

Neutron production from d + A interactions occurs via the following processes: deuteron elastic (or diffractive) breakup and proton stripping processes, sequential neutron emission from highly excited compound and residual nuclei, and so on. In particular, treatment of deuteron breakup processes is important for predicting nucleon emission spectra because the deuteron itself is very loosely bound system. The purpose of this work is to propose a model calculation method that is capable of describing the inclusive nucleon emission quantitatively with no adjustable parameter, and to analyze recent experimental deuteron breakup reactions on ^{7}Li and ^{12}C for energies up to 100 MeV.

In our early work [2], the continuum discretized coupled channels (CDCC) method was applied successfully to the analysis of deuteron elastic scattering from ^{6,7}Li and deuteron reaction cross sections in the energy range up to 50 MeV. The CDCC method [3–5] deals with the deuteron breakup processes explicitly using a three-body Hamiltonian in which the nucleon-nucleus interaction is represented by the optical model potential (OMP) at half the deuteron incident energy and an effective nucleon-nucleon potential is used for the p-n interaction. The CDCC method have so far been applied successfully to analysis of the elastic breakup process in coincidence (d, pn) measurements [4]. It is expected, therefore, that the CDCC method is reliable to predict the elastic breakup component in the inclusive nucleon emission.

However the present version of the CDCC code [6] cannot deal with the proton stripping. Thus, we apply the Glauber model [7] to the calculation of proton stripping process. Up to now, the Glauber model has been widely used in analyses of projectile breakup of exotic and halo nuclei at intermediate energies [8–10]. Also there are some examples of d-induced reactions at intermediate energies above 40 MeV/nucleon in Refs. [11,12]. Since the eikonal phase shift in the Glauber model can be calculated using the nucleon OMP, there is an advantage that no adjustable parameter is included in our Glauber model calculation.

In this paper, some results are presented for our model analyses of (d, xp) reactions on light target nuclei, ^{7}Li and ^{12}C, at 100 MeV. It should be noted that the other results of ^{7}Li have been reported in Ref. [13].

2 Theoretical model

Inclusive nucleon emission spectra from deuteron-induced reactions contain contributions from various reaction processes: the direct processes, *i.e.* elastic breakup and stripping processes, and the statistical decay processes, *i.e.* preequilibrium and evaporation processes. We propose the following model approach [13] to analyze the experimental data of d-induced reactions. For the direct processes, the CDCC method is applied to calculation of the elastic breakup (EB) process and the Glauber model is used for that of the nucleon stripping processes (STR) in the continuum. Also the moving source (MS) model [14] is used to estimate the evaporation and preequilibrium components (EP). We assume that the double differential cross section (DDX) of (d, xp) reactions is described by the incoherent summation

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of three components:

$$\frac{d^2\sigma^{(d,xp)}}{dE_p^L d\Omega_p^L} = \left.\frac{d^2\sigma_{\rm EB}}{dE_p^L d\Omega_p^L}\right|_{\rm CDCC} + \left.\frac{d^2\sigma^n_{\rm STR}}{dE_p^L d\Omega_p^L}\right|_{\rm Glauber} + \left.\frac{d^2\sigma_{\rm EP}}{dE_p^L d\Omega_p^L}\right|_{\rm MS}, \tag{1}$$

where the superscript, L, stands for physical quantities in the laboratory system. The DDX of (d, xn) reactions can also be calculated by replacing the subscript p by n and the superscript n by p in Eq. (1). Since each model has been described in Ref. [13], the outline is given below.

Here let us consider the case where a proton is detected via the elastic breakup process, d+A → p+n+A. The double differential cross section with respect to the proton emission energy and angle is expressed by

$$\left.\frac{d^2\sigma_{\rm EB}}{d\Omega_p^L dE_p^L}\right|_{\rm CDCC} = \frac{2\pi}{\hbar}\frac{\mu_{d{\rm A}}}{P_d}\int d\Omega_n^L |T_{fi}|^2 \rho(E_p^L), \tag{2}$$

in which Ω_p^L and Ω_n^L represent the emission direction of p and n respectively, E_p^L is the proton emission energy, $\mu_{d{\rm A}}$ is the reduced mass of the deuteron and the target, P_d is the momentum of the incident deuteron, and $\rho(E_n^L)$ is the three-body phase space factor [15]. The transition matrix element, T_{fi}, is given in Ref [13].

The Glauber model [7], as a semiclassical approach, gives a rather good prediction of the reaction cross sections involving the loosely bound projectiles, by assuming the eikonal and adiabatic approximations. The differential cross section for the neutron stripping process is given by the following expression [9]:

$$\frac{d\sigma^n_{\rm STR}}{d\mathbf{k}_p^C} = \frac{1}{(2\pi)^3}\int d^2\mathbf{b}_n \left\{\left[1 - |S_n(b_n)|^2\right] \times \left|\int d^3\mathbf{r}\, e^{-i\mathbf{k}_p^C\cdot\mathbf{r}} S_p(b_p)\psi_{00}(\mathbf{r})\right|^2\right\}, \tag{3}$$

in the center of mass of p-n system, where b_p and b_n are the impact parameters of proton and neutron perpendicular to the z axis, $\mathbf{r}$ is the relative cordinate between the proton and neutron in the deuteron, and $\mathbf{k}_p^C$ is the proton wave number vector. The S-matrices for the nucleon-target interaction, S_ν $(\nu = p, n)$, are defined by

$$S_\nu(b_\nu) = e^{i\chi_{\nu{\rm A}}(b_\nu)} = \exp\left[-\frac{i}{\hbar v}\int_{-\infty}^{+\infty} dz\, V_{\nu{\rm A}}\left(\sqrt{b_\nu^2 + z^2}\right)\right], \tag{4}$$

where the phenomenological OMP [2,16] is used for $V_{\nu{\rm A}}$ in the present work. Since the integral in Eq. (4) for the Coulomb part of the proton OMP diverges, we use the same prescription as in Ref. [17], in which the Coulomb eikonal phase shift is added to the $\chi_{p{\rm A}}(b_p)$ calculated using $V_{p{\rm A}}$ without the Coulomb potential. Finally, the double differential cross section of the neutron stripping process can be given by transforming the Eq. (3) from the center-of-mass system to the laboratory system:

$$\left.\frac{d^2\sigma^n_{\rm STR}}{dE_p^L d\Omega_p^L}\right|_{\rm Glauber} = \frac{m_p k_p^L}{\hbar^2}\frac{d\sigma^n_{\rm STR}}{d\mathbf{k}_p^C}, \tag{5}$$

where E_p^L, k_p^L, and Ω_p^L are the energy, the wave number, and the solid angle of the proton in the laboratory system, respectively.

An empirical method based on experimental data, called the moving source (MS) model [14], is applied to estimate nucleon emission via statistical decay processes. The following MS formula is used to calculate the proton DDX of these components in Eq. (1):

$$\left.\frac{d^2\sigma_{\rm EP}}{dE_p^L d\Omega_p^L}\right|_{\rm MS} = \sum_{i=1,2} N_{0,i}\sqrt{E_p^L}\exp\left\{-\left[E_p^L + E_{1,i} - 2\sqrt{E_p^L E_{1,i}}\cos\theta_p^L\right]/T_i\right\}, \tag{6}$$

where the parameters, $N_{0,i}$, $E_{1,i}$, and T_i, are determined by fitting the experimental DDXs at backward angles because the contribution from the direct process is expected to be very small. The suffixes, $i = 1$ and 2, represent the evaporation and preequilibrium processes, respectively.

3 Results and Discussion

Inclusive (d, xn) and (d, xp) reactions on ^{7}Li and (d, xp) reactions on ^{12}C for energies up to 100 MeV are analyzed by using the models outlined in Section 2. The CDCC calculations are performed using the codes [4,6] with the same input data as in our preceding work on deuteron elastic scattering from ^{6,7}Li [2]. The major input data necessary in the Glauber model calculation are the nucleon OMP and the deuteron ground state wave function, which are the same as in the CDCC calculation. Both the CDCC and Glauber model calculations use the extended Chiba OMP for ^{7}Li [2] and the nucleon OMP of Koning and Delaroche [16] for ^{12}C at half the incident deuteron energy.

Figures 1 and 2 shows comparisons between the model calculation and the experimental data of double differential (d, xp) cross sections at small angles up to 20° for the incident energy of 100 MeV [18]. The angular distribution for ^{7}Li is also presented in Fig. 3. It should be noted that the calculation for the ^{7}Li(d, xp) reaction is compared with the experimental data of ^{9}Be in Fig. 1, because the deuteron reaction cross sections calculated using the empirical formula [19] have a modest 12% difference between ^{7}Li and ^{9}Be and both the (d, xp) measurements are expected to provide similar cross sections of deuteron breakup reactions. The parameters of the MS model were determined by fitting the experimental data at 100° where direct breakup contribution is expected to be negligible. The result of ^{7}Li is shown with the MS model parameters in Ref. [13]. The similar result was obtained for ^{12}C, and only the preequilibrium component was enough to reproduce the energy spectrum over the wide emission energy. The following MS model parameters for ^{12}C are obtained: $(N_0, E_1, T) = (1.18, 2.58, 8.30)$.

As shown in Figs. 1 and 2, the model calculations are in excellent agreement with the experimental data for small angles up to 20°. The prominent bump observed around 50 MeV is reproduced fairly well by the calculation for each

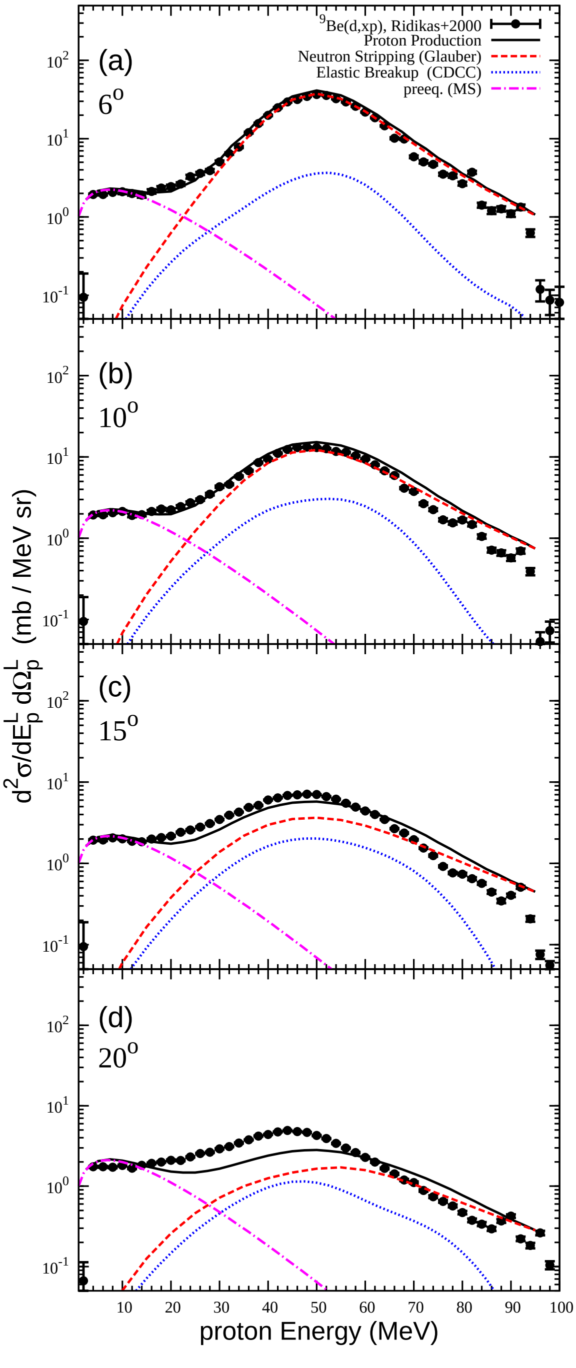

Fig. 1. Comparison of the calculated DDXs of ^{7}Li(d, xp) at 100 MeV with the experimental data [18] of ^{9}Be(d, xp) at 100 MeV for different proton emission angles.

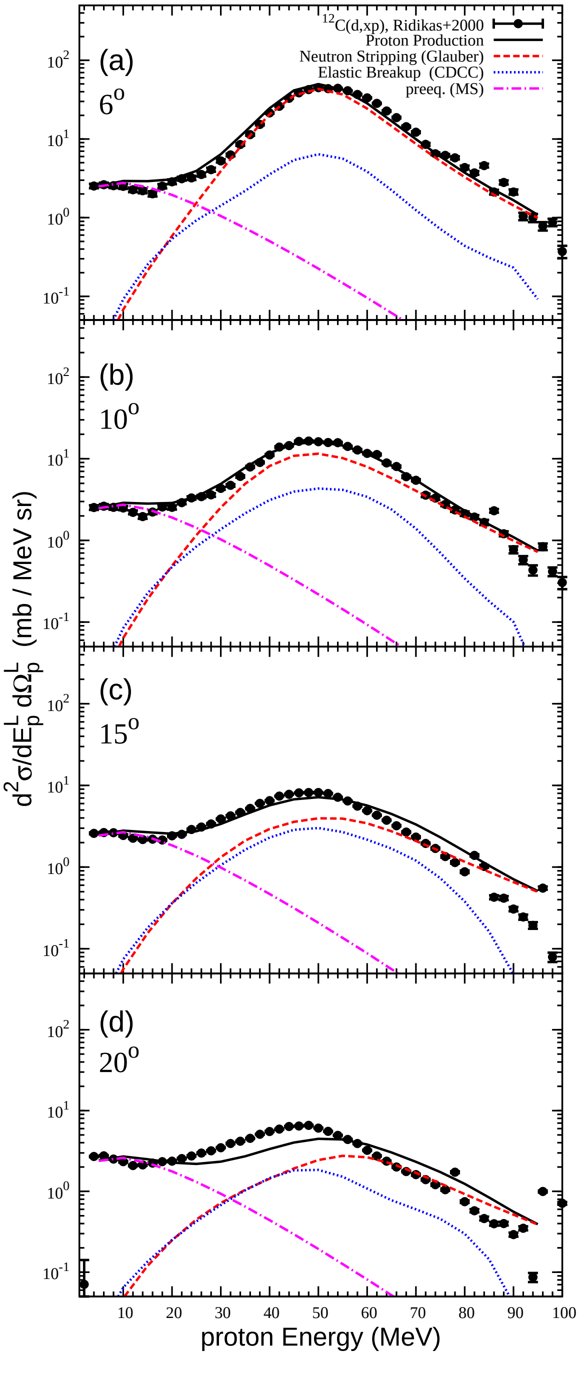

Fig. 2. Comparison of the calculated DDXs of ^{12}C(d, xp) at 100 MeV with the experimental data [18] for different proton emission angles.

angle except at 20°. The neutron stripping process dominates over the elastic breakup process at small angles, and the relative fraction is reduced with increasing emission angle. Note that the Coulomb breakup of the deuteron is not included in the present calculation, because Ridikas *et al.* [18] show a negligibly small contribution from the Coulomb breakup for ^{9}Be. Fig. 3 clearly shows that the deuteron breakup processes is dominant over proton production at forward angles and the statistical decay processes have a major contribution at large angles. Although our model calculation reproduces successfully well the experimental data at small angles, the Glauber model calculation shows that the peak position in the emission spectra shifts to high energy as the emission angle increases, and fails to reproduce the experimental spectra at intermediate angles. Note that the trend appears at 20° as can be seen

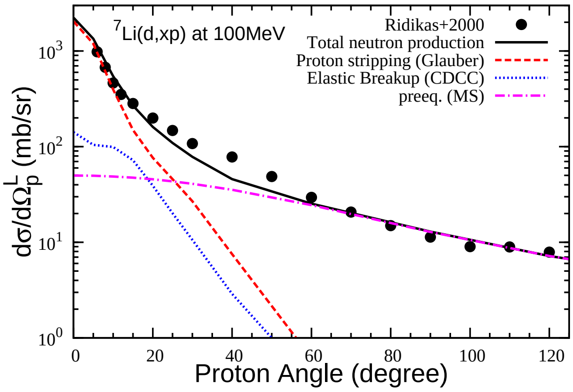

Fig. 3. The same as in Fig.1 but for the angular distribution.

in Figs. 1 and 2. This may suggest a limitation of applying the Glauber model to large momentum transfer.

The CDCC and Glauber model calculations were also applied to analyses of the continuum energy spectra of neutrons produced from the ^{7}Li(d, xn) reaction at 40 MeV, which is regarded as a candidate reaction to produce intense neutron beams. The result has been reported in Ref. [13]. The calculation reproduced the prominent bump observed around 20 MeV in the experimental spectra fairly well. It was found that the deuteron breakup processes are strongly involved with the formation of the bump and the proton stripping process is more predominant than the elastic breakup process. Moreover, it was confirmed that the Glauber approximation is satisfied even at relatively low energy of 40 MeV because the stripping reaction takes place predominantly in the peripheral region of the target nucleus ^{7}Li and the potential depth between deuteron and ^{7}Li around the surface is sufficiently smaller than the incident energy.

4 Summary and conclusions

The deuteron breakup reactions on ^{7}Li and ^{12}C at incident energies up to 100 MeV were analyzed using the model calculation with the CDCC theory for the elastic breakup process, the Glauber model for the stripping process, and the moving source model for the statistical decay processes. The calculations reproduce the experimental energy spectra in the continuum at small angles of less than 20° quantatively well.The analysis showed that the stripping process is dominant over the elastic breakup process.

In the future, we plan to extend the present analysis to (d, xp) reactions on heavier target nuclei. It is expected that the Coulomb dissociation of the deuteron plays an essential role in nucleon emission in very forward direction. Also, it will be necessary to deal with the statistical decay processes properly by using the preequilibrium and Hauser-Feshbach models, instead of the moving source model.

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