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INVESTIGATION OF THE INTERMEDIATE-ENERGY DEUTERON BREAKUP REACTION*

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ABSTRACT

The Udagawa-Tamura formalism is employed to calculate the proton singles both in the bound and unbound regions. Both the Elastic-Breakup (EB) and the Breakup-Fusion (BF) processes are considered to calculate the doubly-differential cross section for light and intermediate mass nuclei. The calculated spectra for 25 and 56 MeV deuterons reproduce the experimental spectra very well except for the spectra at large angle and at low energies, of the outgoing particle. Contributions due to precompound and evaporation processes are estimated to supplement the spectral results based on the Elastic-Breakup and Breakup-Fusion mechanisms. An extension of the model calculations to higher deuteron energies is being made to test the (EB + BF) model limitations.

INTRODUCTION

Intermediate energy nucleon induced neutron and proton spectra have been successfully interpreted in terms of the Intranuclear Cascade model and the evaporation model. Similarly the precompound and evaporation models have been successful in interpreting the nucleon spectra measured in the nucleon induced and heavy ion induced reactions. However, the application of the models to light ions especially to deuteron induced nucleon spectra has had limitations due to the breakup of the projectile within the nuclear

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and coulomb fields. The nuclear reaction model predictability of the deuteron induced neutron and proton spectra at intermediate projectile energy is highly desirable in the application area. The study of deuteron breakup reaction is being extended to intermediate energies following a successful interpretation of the medium energy data.

We aim to develop systematics of deuteron induced nucleon spectra over a wide range of projectile energy and target mass for use in the application area. Towards achieving such a goal we have undertaken the study of deuteron breakup mechanism. The breakup aspects of the deuteron induced reaction have been studied by Udagawa and Tamura¹, (UT) and Bauer et al². We make use of the UT formalism to calculate the proton singles spectra both in the bound and unbound regions. Contributions due to precompound and evaporation process are estimated to supplement the predictions based on breakup mechanism. Preliminary results of our study were presented at the APS/DNP Santa-Fe meeting³.

REACTION MECHANISMS

Depending on the energy of the projectile, different reaction mechanisms have to be considered in fully describing the reaction process. In the case of deuteron at 25 to 200 MeV and beyond the following mechanism may be relevant:

1. Breakup-Fusion
2. Evaporation
3. Precompound

1. Breakup-Fusion:

Over the past few years Udagawa and Tamura have extended their MSDR approach to include light/heavy ion breakup-fusion mechanism for calculating both the bound region and continuum spectra of outgoing particles.

The breakup-Fusion of the deuteron reaction may be symbolically written as:

$$d + A \rightarrow p + n + A \quad [\text{Elastic Breakup (EB)}] \quad (1)$$

$$p + n + A \rightarrow p + B \quad [\text{Breakup-Fusion (BF)}] \quad (2)$$

The sum of partial cross sections for EB and BF processes is:

$$\frac{d^2\sigma^{DR}}{dE_p d\Omega_p} = \sum_{\ell_n j_n} = \frac{d^2\sigma_{\ell_n j_n}^{DR}}{dE_p d\Omega_p} = \sum_{\ell_n j_n} \frac{d^2\sigma_{\ell_n j_n}^{EB}}{dE_p d\Omega_p} + \sum_{\ell_n j_n} \frac{d^2\sigma_{\ell_n j_n}^{BF}}{dE_p d\Omega_p} \quad (3)$$

See ref. 1 for details regarding the evaluation of the EB and BF cross sections.

The Elastic Breakup process is relevant only for the outgoing proton energy above zero ($E_p > 0$), where as the Breakup Fusion cross section must be evaluated both for positive and negative values of E_p . For $E_p < 0$ the Breakup-Fusion cross section is just the stripping (DWBA) cross section to the discrete states in the bound region.

2. Evaporation and Precompound:

For a proper description of the particle spectra in the low and intermediate energy range both the evaporation and precompound mechanisms have to be considered in addition to the direct reaction process. In the present study we make use of Weisskopf-Ewing evaporation theory along with Blann's Geometry dependent hybrid model.⁴

MODEL CALCULATIONS

For the purpose of comparing the theoretical calculated doubly-differential cross sections with the relevant experimental data, the total reaction cross section is decomposed as:

$$\sigma_R = \sigma^{DR} + [\sigma^{PE} + \sigma^{CN}] = [\sigma_{dp} + \sigma_{dn} + \sigma_{dd'} + \dots] + [\sigma^{PE} + \sigma^{CN}] \quad (4)$$

In the present study we calculate σ_R , σ_{dp} , σ^{PE} and σ^{CN} and make some assumptions regarding σ_{dn} ($\approx \sigma_{dp}$) and $\sigma_{dd'}$ (a few percent of σ_R) and normalize the sum ($\sigma^{PE} + \sigma^{CN}$) to $(\sigma_R - \sigma^{DR})$ before adding the corresponding contribution to the UT Breakup-Fusion theory calculated doubly-differential cross sections.

Blann's OVERLAID ALICE code⁴ was used to estimate the precompound and evaporation contribution to the total reaction cross section for (d, p) spectra. No parameter variation was entertained in exciton and evaporation model calculations with ALICE code. The ALICE code predicted cross sections were normalized to account for the σ^{DR} part of total reaction cross section.

We present a comparison of the Breakup-Fusion plus Exciton and Evaporation model calculated results for the following cases:

1. $^{62}\text{Ni}(d, p), E_d = 25.5 \text{ MeV}$
2. $^{27}\text{Al}(d, p), ^{58}\text{Ni}(d, p), E_d = 56 \text{ MeV}$

Figure 1 taken from ULT's paper¹ presents a comparison of ^{62}Ni (d, p) experimental and calculated spectra for $E_d = 25.5 \text{ MeV}$ and $\Theta_p = 20^\circ$. The smooth curve generated by ULT required a normalization factor of 1.2 to fit the experimental data, however the low-energy data were not reproduced well. The dashed curve which includes the contribution due to precompound and evaporation processes does fit the data well without requiring any normalization factor.

For the $^{58}\text{Ni}(d, p)$ spectra at $E_d = 56 \text{ MeV}$ and $\Theta = 9.5^\circ$ and $\Theta = 30^\circ$ the sum of EB and BF contribution is compared with the corresponding experimental data in figure 2a. Figure 2b presents a similar comparison for ^{27}Al (d, p) forward angle spectra. The agreement between theory and experiment is quite satisfactory.

At $E_d = 56 \text{ MeV}$ the evaporation contribution is negligible and precompound emission contribution is also not as important in the quasi-elastic bump region as it is at a lower deuteron energy.

SUMMARY AND FUTURE IMPROVEMENTS

Based on the test cases studied, the UT Breakup-Fusion reaction formalism for deuteron breakup supplemented with the precompound and evaporation mechanisms does reproduce the deuteron induced proton double differential spectra for $E_d \leq 56 \text{ MeV}$. In the present study only the low angle data have been investigated. Only recently some

intermediate-energy deuteron induced neutron spectra both at forward and backward angles have become available. We are extending the model calculations to higher deuteron energies and to heavier targets.

The inelastic breakup and Coulomb effects become important with increasing deuteron energy and target mass and, we plan to pursue these aspects of deuteron breakup mechanism. In addition the ambiguity of the optical model potential will be minimized by making use of local equivalent potentials derived by Mishra et al⁵.

FIGURE CAPTIONS

Fig. 1a. ^{62}Ni (d, p), $E_d = 25.5$ MeV; proton spectra at $\Theta_p = 20^\circ$. The solid and dashed curves correspond to Breakup-Fusion calculated results without and with the inclusion of precompound and evaporation contributions.

Fig. 1b. ^{58}Ni (d, p) $E_d = 56$ MeV; Proton spectra at $\sim 10^\circ$ and 20° . The curves correspond to EB + FB calculated results.

Fig. 1c. ^{27}Al (d, p) $E_d = 56$ MeV; Proton spectra at $\sim 10^\circ$ and 30° . The curves correspond to EB + FB calculated results.

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