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# A Theoretical Study of Deuteron-induced Surrogate Reactions

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**Abstract.** We use the zero-range post-form DWBA approximation to calculate deuteron elastic and nonelastic breakup cross sections and estimate the breakup-fusion cross section that could serve as a surrogate for a neutron-induced reaction cross section. We compare the angular momentum dependence of the breakup-fusion compound nucleus formation cross section with that of the corresponding neutron-induced cross section.

## 1. Introduction

Deuteron-induced reactions have long been studied as substitutes - surrogates - for neutron-induced reactions [1, 2]. Competition between elastic and inelastic breakup, absorption of only a neutron or a proton and absorption of the deuteron must be taken into account to determine the formation or not of a compound nucleus. The breakup-fusion reactions, in which either only a neutron or a proton is absorbed, form compound nuclei with a wide range of excitation energies and angular momenta, but are the cross sections of interest as surrogates. Such measurements of the  $^{238}\text{U}(\text{d}, \text{pf})$  cross section have been performed recently [3, 4, 5]. A theoretical estimate of this cross section requires the cross section for deuteron breakup - neutron fusion with the target. We estimate this by the nonelastic breakup cross section and compare its angular momentum dependence with the corresponding neutron-induced CN formation cross sections.

## 2. The nonelastic and breakup-fusion cross sections

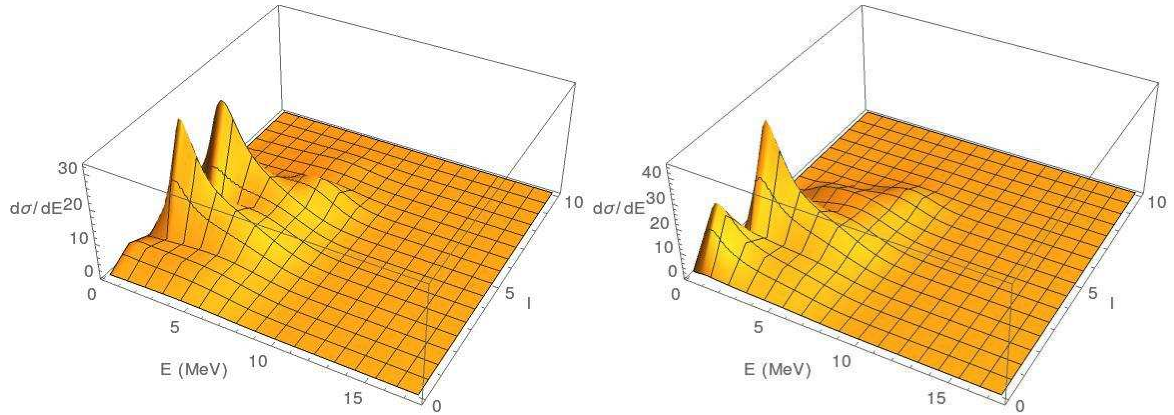
The inclusive proton emission cross section from breakup can be separated into an elastic and nonelastic part [6, 7], denoted here by *bu* for elastic breakup and *bf* for nonelastic breakup, as

$$\frac{d^3\sigma}{dk_p^3} = \frac{d^3\sigma^{bu}}{dk_p^3} + \frac{d^3\sigma^{bf}}{dk_p^3}. \quad (1)$$

The contribution due to elastic breakup is the double differential elastic breakup cross section [8, 9] integrated over the neutron momentum. The nonelastic breakup cross section takes the form of an expectation value of the imaginary part of the optical potential,

$$\frac{d^3\sigma^{bf}}{dk_p^3} = -\frac{2}{\hbar v_d} \frac{1}{(2\pi)^3} \left\langle \Psi_n(\vec{k}_p, \vec{r}_n; \vec{k}_d) \left| W_n(\vec{r}_n) \right| \Psi_n(\vec{k}_p, \vec{r}_n; \vec{k}_d) \right\rangle, \quad (2)$$





**Figure 1.** (a) Energy - angular momentum distribution of  $(d, p)$  differential CN formation cross section for 20 MeV deuterons incident on  $^{238}\text{U}$ . (b) Renormalized partial wave cross section for neutrons incident on  $^{238}\text{U}$ .

where the effective neutron wave function is given by

$$\left| \Psi_n(\vec{k}_p, \vec{r}_n; \vec{k}_d) \right\rangle = \left( \tilde{\psi}_p^{(-)}(\vec{k}_p, \vec{r}_p) G_n^{(+)}(\vec{r}_n, \vec{r}_n') |v_{pn}(\vec{r})| \psi_d^{(+)}(\vec{k}_d, \vec{R}) \phi_d(\vec{r}) \right). \quad (3)$$

This wave function can be well-approximated in the zero-range approximation by including the finite range correction of Ref. [10].

To perform numerical calculations as well as to obtain CN formation cross sections, the wave functions and matrix elements are expanded in partial waves. The deuteron breakup - neutron fusion cross sections at a given value of the neutron orbital angular momentum and kinetic energy are estimated by summing the nonelastic breakup partial wave cross sections over the possible values of the deuteron and proton angular momenta.

The Koning-Delaroche global optical potentials [11] are used in the proton and neutron channels while the potential of Ref. [12] is used to describe the deuteron scattering. The elastic breakup matrix elements are only conditionally convergent. The most efficient means of performing the integrals is their extension to the complex plane[13], which usually limits the numerical integration to at most several hundreds of fm.

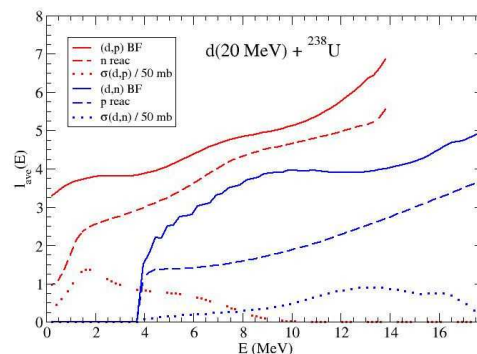
Inclusive elastic and nonelastic  $(d, p)$  and  $(d, n)$  breakup cross sections have been calculated recently by our group in the post form, as well as by others, using both the prior and post forms of the DWBA and have verified their consistency [14, 15, 16, 17]

### 3. $(d, p)$ breakup-fusion as a surrogate neutron-induced reaction

To more easily compare the neutron reaction cross section with the nonelastic  $(d, p)$  breakup cross section, shown in the left panel of Fig. 1 as a function of neutron energy and orbital angular momentum for a deuteron energy of 20 MeV, we have renormalized the former so as to reproduce the angular momentum summed nonelastic  $(d, p)$  cross section as a function of the neutron energy,

$$\frac{d\tilde{\sigma}_n}{dE}(E, l) = \frac{d\sigma_{(d,p)}}{dE} \frac{\sigma_n(E, l)}{\sigma_n(E)} \quad (4)$$

The renormalized neutron reaction cross section is shown in the right-hand panel of Fig. 1. We immediately observe the greater extension in angular momentum of the inclusive nonelastic  $(d, p)$  cross section. To better quantify the difference, we compare the average angular momenta of the distributions as a function of the neutron energy  $E$ , shown by the red curves in Fig. 2.



**Figure 2.** Average angular momentum as a function of energy of the inclusive  $(d,p)$  and neutron reaction cross sections (in red). The scaled  $(d,p)$  differential cross section is also shown for reference. The corresponding  $(d,n)$  and proton reaction cross sections are shown in blue.

We observe that the difference in average angular momentum of the  $(d,p)$  and neutron reaction cross sections is largest at low neutron energy, but is still about one unit of angular momentum in the region of the energy peak of the  $(d,p)$  reaction. A similar conclusion holds for the  $(d,n)$  reaction and a proton-induced one, as can be seen by comparing the blue curves in the figure.

We thus find that a  $(d,p)$  reaction typically furnishes more angular momentum to the compound nucleus than a neutron-induced reaction at the same neutron energy. This difference limits the extent to which the  $(d,p)$  reaction can substitute a neutron-induced one. A more complete study of these effects is in progress.

### Acknowledgments

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