

Systematic Study of Deuteron-induced Reactions from Threshold

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Deuteron induced reactions are studied systematically using the Glauber model. The trajectory modification is employed for analyses from threshold energies by taking into account a proper closest approach with Coulomb and nuclear interactions. Comparisons between experimental data and calculations with the optical model and the CDCC method support the effectiveness of the trajectory modification in the Glauber model.

I. INTRODUCTION

Deuteron induced reactions have attracted much interest in association with various neutron applications in recent years, due to the fact that they have a capability of producing high-intensity neutrons. One of the applications is in neutron irradiation tests of fusion reactor candidate materials, which are planned in the International Fusion Material Irradiation Facility (IFMIF). In the engineering design of such neutron sources and accelerator shielding, knowledge of the nuclear interactions of deuterons with materials is indispensable to estimate neutron yields and induced radioactivity. Thus, systematic studies of deuteron-induced reactions are desirable to produce reliable deuteron data over a wide range of incident energies and target mass numbers.

Because the deuteron is a loosely bound nucleus, the breakup effect shall be taken into account in many reaction processes to produce reasonable nuclear data set. Till now, no theoretical method can deal with deuteron breakup effect very well for all reaction processes, although the Continuum-Discretized Coupled Channel (CDCC) method [2] works well for the elastic breakup process only. Recently, we had proposed an effective approach [3] which describes well the double differential cross section (DDX) and the angular distribution of the inclusive (d, xn) and (d, xp) reactions. The CDCC method and the Glauber model are employed to describe the elastic breakup and the stripping processes, separately, in which the breakup effects are important. We focus on the Glauber model in the present work.

II. GLAUBER MODEL

The Glauber model [1], as a semiclassical approach, describes rather well on elastic scattering problem by assuming a straight-line trajectory along the incident direction for projectile at high energies. In the case of deuteron induced reaction, the Glauber model includes the breakup effect naturally by considering the neutron-target and proton-target phase shifts, separately. Besides at high energies, the deuteron data at low energies are also necessary for application. However, the straight-line trajectory doesn't hold any more at low energy when the projectile is close to the target nucleus because of the strong influence from the Coulomb and nuclear forces. The modified trajectory at the distance of closest approach rather than the impact parameter was proved to work well for heavy-ion collisions from a few MeV/nucleon [4]. This method is applied to the analysis of deuteron induced reactions in this work.

For more precise predictions of deuteron induced reactions, Glauber model calculations are performed using the nucleon optical potential (OP) [5, 6] and the deuteron wave function obtained from a Gaussian potential rather than a microscopic model at deuteron incident energies from threshold to 200 MeV, because the OP contains more realistic information about nucleon-nucleus (NA) interaction. The same nucleon OP is also employed as the nuclear potential necessary in the trajectory modification. Thus, the present model has no free parameters.

The total reaction cross section of deuteron-nucleus (dA) collisions is expressed as

$$\sigma_R = \int d\vec{b} \left[1 - \left| \langle \psi_{00} | e^{i\chi(b)} | \psi_{00} \rangle \right|^2 \right], \quad (1)$$

where ψ_{00} is the deuteron ground state wavefunction, b is the impact parameter and, χ is the phase-shift function defined by the Glauber model.

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With the eikonal approximation, the phase-shift can be connected with projectile-target optical potential (OP) by a simple formula

$$\chi(b) = -\frac{1}{\hbar v} \int_{-\infty}^{+\infty} dz V_{\text{OP}} \left(\sqrt{b^2 + z^2} \right), \quad (2)$$

where v is the velocity of the projectile, z is the axis along the incident direction of the projectile, and V_{OP} is the complex optical potential.

Because the deuteron is a composite nucleus, the Few-Body Glauber (FBG) model [7] should be applied to calculate the optical phase-shift (i.e., elastic S-matrix) for deuteron-nucleus scattering. In the FBG model, the total phase-shift is given as the sum of the phase-shifts for

scattering of a proton and a neutron in the deuteron from the target nucleus

$$e^{i\chi(b)} = \exp [i\chi_{\text{pA}}(b_p) + i\chi_{\text{nA}}(b_n)], \quad (3)$$

where b_p and b_n are the coordinate projection of the proton and neutron perpendicular to the z direction.

According to Eqs. (2) and (3), the total phase-shift can be calculated using the NA-OP. There are two kinds of OPs: the phenomenological OP and the OP constructed using Optical Limit (OL). In the present work, the former is chosen for the sake of simplicity and comprehensiveness.

Using the FBG model, the total reaction cross section of dA collision and the elastic breakup (elBU) cross section can be expressed by

$$\begin{aligned} \sigma_R &= \int d\vec{b} \left[1 - \left| \langle \psi_{00} | e^{i\chi_{\text{pA}}(b_p) + i\chi_{\text{nA}}(b_n)} | \psi_{00} \rangle \right|^2 \right] \\ \sigma_{\text{elBU}} &= \int d\vec{b} \left\{ \left| \langle \psi_{00} | e^{i\chi_{\text{pA}}(b_p) + i\chi_{\text{nA}}(b_n)} | \psi_{00} \rangle \right|^2 - \left| \langle \psi_{00} | e^{i\chi_{\text{pA}}(b_p) + i\chi_{\text{nA}}(b_n)} | \psi_{00} \rangle \right|^2 \right\}. \end{aligned} \quad (4)$$

The eikonal approximation has been validated at high incident energies. However, a modification is necessary to reproduce experimental data at low energies, since the nuclear and Coulomb potentials have much stronger effects on the projectile trajectory than those at high energies. Because the phase-shift is sensitive to b around the surface of target nucleus, the precise closest approach shall be applied in Eq. (4) to give more precise prediction on the cross sections.

III. RESULTS AND DISCUSSION

The effectiveness of the trajectory modification on Glauber model has to be tested at first. The deuteron reaction cross section for ^{58}Ni are shown in Fig. 1 with the experimental data. As expected, the modified Glauber model with curved trajectory derived by both Coulomb and nuclear interactions shows good agreement with the whole experimental data and becomes a straight line at deuteron energies larger than 25 MeV per nucleon. Meanwhile, the result with only Coulomb interaction shows a clear underestimation. Moreover, it should be noted that better agreement between the present Glauber model and the optical model is also obtained for proton reaction cross sections.

The present Glauber calculations with a trajectory modification for deuteron reaction cross sections are compared with experimental data, CDCC calculations, and deuteron optical model calculations [8] for six targets, ^7Li , ^{12}C , ^{58}Ni , ^{90}Zr , ^{120}Sn , and ^{208}Pb at energies from threshold to 100 MeV/A in Fig. 2. The CDCC calculations are performed using the same codes as those in Ref. [9]. The Glauber model calculations agree with the optical model calculations fairly well. Both calculations reproduce the experimental data to the same extent.

The calculations of elastic breakup cross section are also shown in Fig. 2. The results of Glauber model and CDCC method are compared, because there is no available experimental data. Both calculations show excellent agreement except at energies lower than 30 MeV/A.

In spite of encouraging results, the theoretical foundation of this semi-classical model is still questionable in the

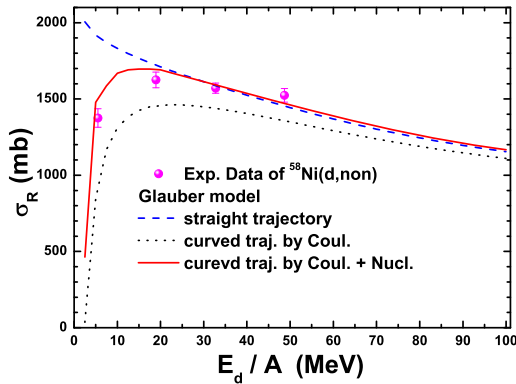


FIG. 1. Effect of trajectory modification of Glauber model on $^{58}\text{Ni}(\text{d}, \text{non})$, the total reaction cross reaction. The experimental data are from EXFOR data library [10].

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