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Thick Target Neutron Production on Aluminum and Copper by 40 MeV Deuterons *

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The thick target neutron yields (TTNYs) of deuteron-induced reaction on Al and Cu isotopes are analyzed by combining the improved nuclear models and particle transport effects. The modified Glauber model is employed mainly to produce the peak of double differential cross section for the breakup process, and the exciton model and the Hauser–Feshbach theory are used for the statistical processes. The thin-layer accumulation method is used to calculate the TTNYs considering the neutron attenuation effects in the target. The calculated results are compared with the existing experimental data, and the analysis method can predict the TTNY data well at the deuteron energy of 40 MeV.

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The neutron production data of the deuteron incident nuclear reactions are the fundamental blocks for the design and analyses of accelerator-based neutron sources and fusion-related facilities. The International Fusion Material Irradiation Facility (IFMIF)[1] is such a large driven force acquiring cross section data and thick target neutron yield data in the energy range from the threshold up to 40 MeV, and so is Neutron For Science (NFS) in SPRIAL2.[2] Among these kinds of facilities, the light nuclei such as Li, Be, and C are set as the target materials to produce high neutron flux for various irradiation purposes. Meanwhile, the deuteron data of the structural materials such as Al and Cu are indispensable for the production of radionuclide, activation analysis of accelerator components, and the study of mechanical wear by surface activation, because a large amount of interactions may occur by deuteron beam loss or direct hit.[3−7] In addition to the activation reactions, the accurate secondary neutron production data are also necessary to estimate the radiation dose.[8]

The nuclear data on these subjects have been measured and simulated by some laboratories for decades. However, the data are still scarce, such as the outgoing neutron angles and the kinds of target materials. Meanwhile, there are discrepancies between the measured and Monte Carlo calculated results. To estimate completely the thick target yield of deuteron-induced reaction, it is necessary to incorporate the theoretical studies of the nuclear models and the particle transportation methods simultaneously.

As the simplest composite nucleus, the deuteron breaks up easily during the interaction with the target nucleus due to its weak binding energy. Different from neutron-induced reactions, two special direct breakup reaction processes are involved in the deuteron-induced reactions, along with the elastic and inelastic scattering processes. The elastic breakup (EB) process, known as (d, np) reaction, emits the neutron and the proton simultaneously with the target nucleus left on its ground state. The stripping process (STR), or the so-called inelastic breakup, projects out a nucleon and the other nucleon interacts with the target strongly. A broad peak structure is shown clearly in the experimental data of double differential cross sections (DDX) and the energy spectra of outgoing nucleons around half the incident energy, which is commonly thought to be the contributions from the breakup processes. Also, the deuteron can react with the target nucleus through the statistical processes, i.e., the pre-equilibrium and compound processes, by which the protons or neutrons are decayed out. Therefore, the inclusive secondary nucleon production reactions, (d, xn) or (d, xp), include the contributions from the direct breakup processes, the pre-equilibrium and the compound processes.

Various theoretical works have been carried out on the breakup reactions. Serber proposed his phenomenological model[9] first in 1947, for the deuteron stripping process. The Glauber model[10] had been developed for the multiple scattering of nucleons in nuclear targets in the 1950s, and discussed the stripping process of deuteron–nucleus collision. Faddeev also discussed a three-body breakup theory[11] in 1961, and a rich literature based on this theory has been developed since then. In the 1970s and early 1980s, numerous works employed the distorted-wave Born approximation (DWBA) method. Baur *et al.*[12] have discussed the post-form of DWBA in detail. Meanwhile, a continuum-discretized coupled channel (CDCC) method[13−15] was proposed, describing the deuteron scattering and elastic breakup reactions rather well.

Recently, the deuteron-induced reactions attracted

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much attention for application purposes, and the inclusive nucleon production reaction is one of the concerned subjects. Our previous work[16,17] suggested a calculation method describing the deuteron-induced inclusive reaction with the CDCC method for the EB process, the Glauber model for the STR process, and the conventional statistical Hauser–Feshbach theory and the two-component exciton model for the statistical processes. The TALYS code[18] was used to calculate the statistical processes. Nakayama *et al.*[19] developed the deuteron-induced reaction analysis code system (DEURACS) for evaluation of deuteron nuclear data by using the same calculation method for the direct breakup processes as Ref. [16], but also included the stripping process to bound states by DWBA and three statistical decay processes, such as (d, xp), (p, xp) and (n, xp). The calculations reproduced fairly well the experimental data on several targets, ^{9}Be, ^{12}C, ^{27}Al and ^{58}Ni, at forward angles with deuteron inducing energies at 25.5, 56 and 100 MeV. In particular, the very good agreement was seen for the main peaks at half the deuteron energy, which shows the dominant contribution of the direct breakup processes and the CDCC+Glauber calculation method worked well. The good agreement with the TTNY experimental data was also seen for ^{9}Be and ^{12}C targets below 50 MeV. By incorporating with the PHITS code, Hashimoto *et al.*[20] proposed a model combining INCL and DWBA for deuteron reactions on the light nuclei (Li, Be, C) below 50 MeV, and DDX and TTNY data of inclusive nucleon reactions were well reproduced. In addition to Ref. [20], a revival of DWBA method on this subject is also presented by another three theoretical works.[21–23]

Though many sophisticated theories were developed, it is a pity that only the combination schemes can describe the whole inclusive breakup reactions properly, even for the direct reactions. Based on the Glauber model, a unified scheme, describing properly the inclusive direct breakup reactions, is proposed and examined preliminarily by using the TTNY data of structural material Al and Cu bombarded with 40 MeV deuterons. For the completeness, the statistical theory is also included in the scheme. Firstly, an improved model calculation is employed to produce the double differential cross sections (DDXs) based on our former work,[17] and then a thin layer accumulation method is used to calculate the TTNY data similar to Wei *et al.*,[24] but includes the neutron attenuation effects in the target.

A brief description is given for the TTNY method. The emitted neutron yield from the thick target can be derived as

$$\frac{d^2Y_n}{d\Omega dE_n}(\theta, E_n, E_{\mathrm{d,I}}) = \int_{E_{\mathrm{d,I}}}^{0} I_0 N_{\mathrm{d}} \frac{d^2\sigma}{d\Omega dE_n}(\theta, E_n, E_{\mathrm{d}}) \frac{1}{S(E_{\mathrm{d}})} dE_{\mathrm{d}}, \quad (1)$$

where $E_{\mathrm{d,I}}$ and I_0 represent the deuteron incident energy and its intensity, respectively, θ is the neutron emission angle. N_{d} is the atomic density of the target nucleus, E_{d} is the deuteron energy inside the thick target, and E_n is the neutron's emission energy, $d^2\sigma/d\Omega dE_n$ is the DDX of deuteron–nucleus reaction, and $S(E_{\mathrm{d}}) = -dE_{\mathrm{d}}/dx$ is the stopping power of the deuteron in the target.

Then, the thick target is treated as the combination of many thin layers for integral. The total neutron yield is the accumulation of the yield from each layer, given as

$$\begin{aligned} &\frac{d^2Y_n}{d\Omega dE_n}(\theta, E_n, E_{\mathrm{d,I}}) \\ &= \sum_i I_i N_{\mathrm{d}} \frac{d^2\sigma}{d\Omega dE_n}(\theta, E_n, E_{\mathrm{d,i}}) \frac{1}{S(E_{\mathrm{d,i}})}) \Delta E_{\mathrm{d,i}}, \quad (2) \\ I_i &= I_{i-1}[1 - \sigma_{\mathrm{non}}(E_{\mathrm{d},i-1})\Delta x_{i-1}]_i \\ &\quad \cdot N_{\mathrm{d}} \frac{1}{S(E_{\mathrm{d},i-1})} \Delta E_{\mathrm{d},i-1}, \\ i &= 1, 2, 3, \ldots, n, \quad (3) \end{aligned}$$

where i is the index of the layer, $E_{\mathrm{d},i}$ is the deuteron inducing energy on the ith layer, $\Delta E_{\mathrm{d},i}$ is the energy loss of deuteron in the ith layer, and Δx_{i-1} is the thickness of the $(i-1)$th layer. The attenuation by nuclear reaction of the deuteron intensity is also included as I_i, where $I_1 = I_0$ is the initial incident deuteron intensity, and $\sigma_{\mathrm{non}}(E_{\mathrm{d,i}-1})$ is the corresponding total reaction cross section of deuteron-target interaction in the $(i-1)$th layer. The value of $\sigma_{\mathrm{non}}(E_{\mathrm{d,i}-1})$ is given by the Glauber model.[25] The comparison between I_0 and I_i shows that the attenuation of nuclear reaction affects the intensity clearly only at the last several layers.

To calculate TTNY data using Eq. (2), the stopping power, $S(E_{\mathrm{d,i}-1})$, and the DDX data, $d^2\sigma/d\Omega dE_n$, are the necessary input. SRIM-2011 code[26] is used to calculate $S(E_{\mathrm{d,i}-1})$ and the range Δx_{i-1} as mentioned in Eq. (3).

The DDX data is calculated by following the method based on our previous work,[17] in which several nuclear models were employed. First, the scattering processes are analyzed. The deuteron optical model (OM) with a global spherical optical potential[27] is employed to determine the total reaction cross section, an OM angular distribution of the elastic scattering, and the transition coefficients, and OM parameters are taken from Eqs. (12) and (13) of Ref. [27]. Meanwhile, the discrete inelastic scattering cross sections are given by the DWBA approach. Secondly, the statistical processes, such as the compound nucleus (CN) and pre-equilibrium (PE) processes, are calculated with the transition coefficients as input, and are described by the Hauser–Feshbach theory and the exciton model, respectively, as in the TALYS code.[18] Then, the two breakup processes (BU), EB and STR, are analyzed by the Glauber model in this work. In

our previous work,[17] the EB process was described by the CDCC method. Finally, the emitted neutron spectrum is given by the incoherent summation of all processes as follows:

$$\frac{d^2\sigma}{d\Omega dE_n} = \frac{d^2\sigma^{\rm EB}}{d\Omega dE_n} + \frac{d^2\sigma^{\rm STR}}{d\Omega dE_n} + \frac{d^2\sigma^{\rm CN+PE}}{d\Omega dE_n}. \quad (4)$$

As proved in our former works,[16,17,19] Eq. (4) with proper theoretical models can reproduce the experimental DDX data well at incident energies from 20 MeV to 100 MeV. However, in the case of the TTNYs analysis, the proper calculations at low energies down to the threshold are required, because the thickness of the experimental target was set to be thick enough to stop the incident beam. At energies below 20 MeV, the Glauber model with the eikonal approximation becomes worse. The Glauber model with trajectory modification (GMTM)[25] is found to reproduce the experimental data of total reaction cross sections even at the low energies near threshold. Such modification is shown to agree well with the CDCC method, also for the calculation of the integrated cross section data of the EB process at energies from threshold. As is expected, the result of GMTM approaches to the eikonal approximation's results with the increasing incident energy.

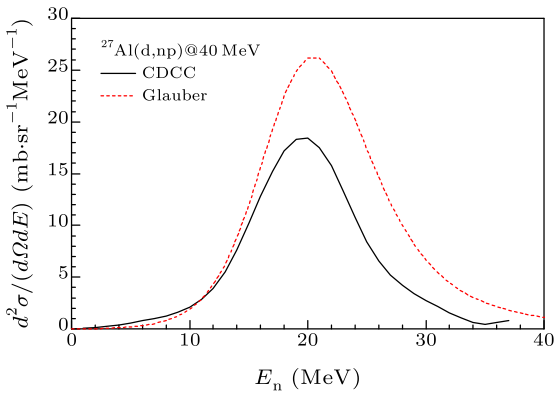

Fig. 1. The comparison of DDX of ^{27}Al(d, np) reaction between the Glauber model (solid curve) and the CDCC method (dashed-dotted curve) at 0° and 40 MeV incident energy. There is no Coulomb breakup included in the CDCC calculation.

We focus on the shape of energy distribution since the DDX data is of interest in this work. In Ref. [16], they show that the STR process given by the Glauber model has a similar distribution shape as the EB process given by the CDCC method for lighter nuclei (^{7}Li, ^{9}Be, ^{12}C, ^{27}Al and ^{58}Ni) at the forward angles around half the deuteron incident energy. The reason may be that the Coulomb breakup process is not strong and the deuteron energy is almost equally distributed between neutron and proton as the Glauber model does. An example is shown in Fig. 1 for ^{27}Al(d, np), i.e., the EB process, at 0° and 40 MeV incident energy. The DDX of the STR process given by the Glauber model is changed by adjusting its integration over angle and energy to the EB cross section, and compared with the DDX of the EB process given by the CDCC method. The shape of energy distribution of the EB process is reproduced by the Glauber model results, and then the Glauber model can give the DDX of the EB process with good approximation by

$$\frac{d^2\sigma^{\rm EB}}{d\Omega dE_n} = \frac{\sigma^{\rm EB}}{\sigma^{\rm STR}} \times \frac{d^2\sigma^{\rm STR}}{d\Omega dE_n}. \quad (5)$$

A deviation can be seen between both the methods in Fig. 1. The reason is that the different S-matrices are used for both the methods, quantum S-matrix for the CDCC method and eikonal S-matrix for the Glauber model. In Ref. [16], the authors discussed the effect of the quantum S-matrix on lead and showed the improvement at forward angles. However, such a deviation will not affect the total BU cross section much because the EB process contributes less than the STR process to total BU cross section. In this work, the eikonal S-matrix is used to speed up the TTNY calculation and to give the preliminary results.

GMTM, with trajectory modification and magnitude adjustment using Eq. (5), presents a tool to analyze the two breakup processes, EB and STR, simultaneously by one theoretical model in a wide energy region from the threshold to 200 MeV. It would be more accurate for lighter nuclei because the effect of Coulomb breakup process becomes weaker with the decreasing target mass. Moreover, GMTM can carry out the quick calculations on the EB process compared with the CDCC method. Because a large set of DDX data are needed for the summations given in Eq. (2) while calculating the TTNY data, GMTM combined with TALYS code would be an efficient tool on TTNY analysis with consistent description on breakup processes.

Figure 2 shows the calculation on the TTNY data of ^{27}Al(d, xn) at 0° and 40 MeV incident energy, which uses the DDX data at 0° from 40 MeV down to the deuteron binding energy, 2.22 MeV, given by GMTM combined with TALYS code. The DDXs data at 0° only are used, because we assume that the DDX data at other angles affect slightly the TTNY data at 0°. The assumption is based on two reasons. First, the (d, xn) reaction has a sharp forward angular distribution as shown in Ref. [16], and secondly the thickness of target is less than 5 mm as defined by the range of energetic deuteron in Al, which is too thin to disturb the angular distribution of neutron flux. In Fig. 2, the curve labeled as Total is the total TTNYs given by Eq. (4), and the Total (adjusted) curve is calculated by fitting Total results with the experimental data at the central peak point, and the Stat. (adjusted) curve is calculated by fitting to the original statistical calculation results (Stat.) to the low energy data below 5 MeV, and the BU (adjusted) curve is the adjusted total breakup (BU) results by keeping the Total (adjusted) curve fitted. Then, the Total (adjusted) curve is the sum of BU (adjusted) and Stat. (adjusted) cur-

ves.

In Fig. 2, the curve labeled as Total is the total TTNYs given by Eq. (4), and the Stat. (adjusted) curve is calculated by fitting the original statistical calculation results (Stat.) to the low energy data below 5 MeV, and the BU (adjusted) curve is calculated by fitting with the experimental data at the central peak point near half the deuteron inducing energy, and finally the Total (adjusted) curve is the sum of BU (adjusted) and Stat. (adjusted). The fitting of BU results is that the original BU results are changed after shifting 2 MeV toward low energy and decreasing 1.45 times of magnitude. After fitting, the Total (adjusted) results reproduce the shape of the experimental data of TTNYs, even though the peak value is the only fitted point there. The relative error, C/E-1, is less than ±10% around the main peak from 10 MeV to 30 MeV. Anyway, the original Total result is not far from the experimental data and can be acceptable because its relative error is less than 50% around the main peak.

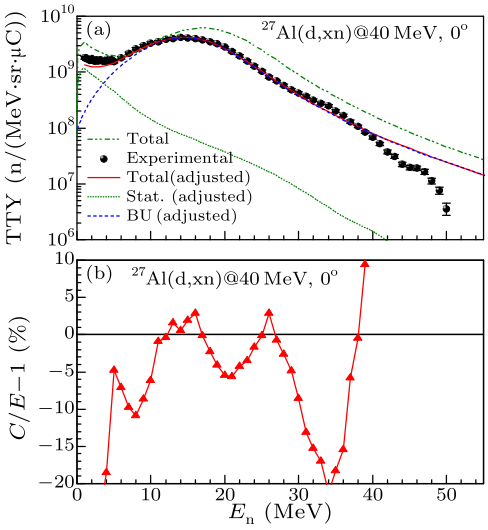

Fig. 2. The TTNY data of ^{27}Al(d, xn) reaction at 40 MeV and 0° are given in the left panel with experimental data[28] (dots), in which the 'Total' (adjusted) (solid curve) result is the sum of 'Stat.' (short-dotted curve) and 'BU' (short-dashed curve) results, and the total (dash-dot-dotted curve) result is the original calculation. In the right panel, the relative error (red-triangle curve) between total (adjusted) result and the experimental data is given.

The similar results can be seen in Fig. 3 for the Cu targets at 40 MeV. The difference of calculations between Al and Cu is that the Total result is higher than the experimental data for Al and lower for Cu. The adjustment on calculations improves the fit with the experimental data and shows the evidence that GMTM can describe the BU processes well. The deviation of calculation from the experimental data means more improvements are necessary. First, the effects of the Coulomb barrier and the deuteron binding energy have to be included later to explain the shift of the peak energy 2 MeV toward low energy. Secondly, the magnitude deviation may come from the deviation on integrated cross sections given by GMTM to the experimental data. As shown in Fig. 2 of Ref. [25], the GMTM results of the total reaction cross section (σ_R) are higher than the experimental data and the OMP results for the lighter nuclei, such as Be and C, at energies above 20 MeV, but lower for the heavier nuclei, such as Ni, Zr, Sn and Pb, in the same energy region. The similar trends are given for the calculation of σ_R on Al and Cu. Finally, the EB process is calculated approximately by the Glauber model instead of the more precise CDCC method.

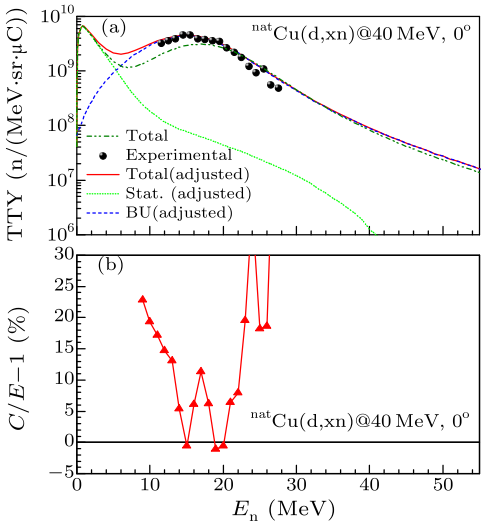

Fig. 3. The TTNY data of ^{nat}Cu(d, xn) reaction at 40 MeV and 0° are given in the left panel with the experimental data[29] (dots), in which the Total (adjusted) (solid curve) result is the sum of Stat. (short-dotted curve) and BU (short-dashed curve) results, and the Total (dash-dot-dotted curve) result is the original calculation. In the right panel, the relative error (red-triangle curve) between the Total (adjusted) result and the experimental data is given.

In summary, we have proposed a unified method for the inclusive direct breakup reactions by the improved Glauber model and the quantitatively good results can be expected according to the preliminary analyses on Al and Cu targets. By including the statistical theories, this method can be used to analyze the DDX and TTNY data of the deuteron-induced reactions down to the threshold. Good results on Al and Cu targets induced by 40 MeV deuterons are given. However, some improvements should be included, such as the breakup energy correction, the improved Glabuer model on σ_R accuracy and the EB process. It is expected that such improvements will make the calculations more reasonable and reliable.

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