Analysis of (d, xn) reactions on ^{9}Be and ^{12}C

S. Nakayama[1], H. Kouno[2], Y. Watanabe[2], O. Iwamoto[1], and K. Ogata[3]
[1] *Nuclear Data Center, Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195, Japan*
[2] *Department of Advanced Energy Engineering Science, Kyushu University, Kasuga, Fukuoka 816-8580, Japan*
[3] *Research Center for Nuclear Physics (RCNP), Osaka University, Ibaraki, Osaka 567-0047, Japan*

In recent years, intensive neutron sources using deuteron accelerators have been proposed for various applications such as transmutation of long-lived radioactive waste [1], production of medically useful radioisotopes [2], and so on. In the design of such neutron sources, accurate and comprehensive nuclear data relevant to deuteron-induced reactions are indispensable over wide ranges of target mass number and incident deuteron energy. Therefore, we have been developing a code system dedicated for the deuteron-induced reactions, called deuteron-induced reaction analysis code system (DEURACS). In our early work, it was successfully applied to systematic analyses of double-differential cross sections (DDXs) of the (d, xp) reactions on ^{12}C, ^{27}Al, and ^{58}Ni at the incident energies of 56 and 100 MeV [3]. As our next step, the purpose of the present work is to investigate the applicability of DEURACS to (d, xn) reactions for incident energies below 50 MeV and to clarify neutron production mechanism. There are few experimental DDXs data of (d, xn) reactions, while some measured data of thick-target neutron yields (TTNYs) from deuteron bombardment on ^{9}Be and ^{12}C are available. Therefore, we derive TTNYs from the DDXs of (d, xn) reactions calculated with DEURACS and discuss the neutron production mechanism through comparisons of the calculated TTNYs with the experimental ones.

DEURACS consists of several calculation codes based on theoretical models to describe respective reaction mechanisms involved in deuteron-induced reactions. First, elastic breakup reaction (EBU) is calculated with the continuum-discretized coupled-channels (CDCC) method [4]. Next, nonelastic breakup reaction (NBU) is calculated with the Glauber model [5, 6]. In the present work, we incorporate a noneikonal approach in the Glauber model as in Ref. [6]. In addition, proton transfer reaction (p-TR) is treated with a conventional distorted wave Born approximation (DWBA) approach. We employ the zero-range DWBA code DWUCK4 [7] for the DWBA calculation. Finally, pre-equilibrium (PE) and compound nucleus (CN) components from highly excited residual nuclei are calculated using the two-component exciton model and the Hauser-Feshbach model implemented in CCONE [8, 9]. See Ref. [10] for more details of the models integrated in DEURACS and the methods to derive TTNYs from DDXs of (d, xn) reactions.

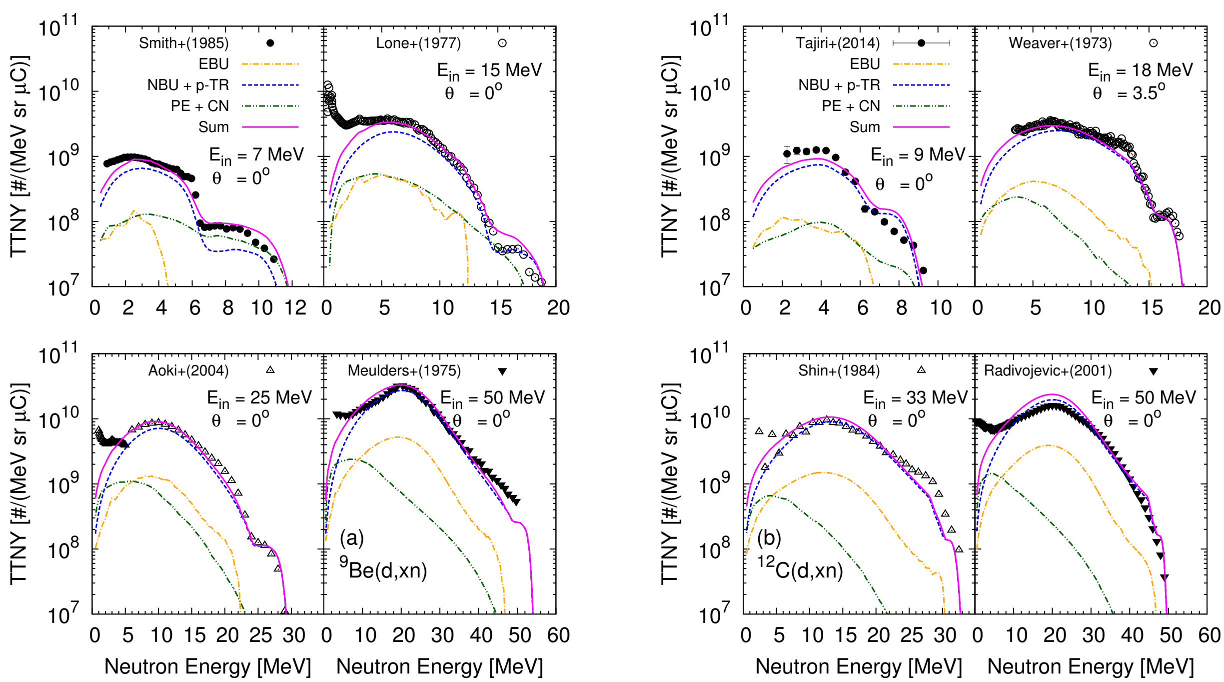

Figure 1: Calculated and experimental TTNYs for (a) the ^{9}Be(d, xn) reactions and (b) the ^{12}C(d, xn) reactions at angles around 0°. The dash dotted, the short-dashed, and the dash-dot-dotted curves represent the component of EBU, NBU+p-TR, and PE+CN, respectively. The solid curves are sums of each component. Experimental data are taken from the EXFOR database [11].

Figure 1 shows comparisons between the calculated and experimental TTNYs on ^{9}Be and ^{12}C targets at angles around 0°. The calculation reproduces both the shape and magnitude of the experimental TTNY data in the wide incident energy range up to 50 MeV. In the figure, characteristic broad peaks can be seen around half the deuteron incident energies. These peaks mainly come from the NBU process. Therefore, it is found that the NBU component makes the most dominant contribution to the neutron production. Our previous (d, xp) analyses [3] also have shown that the NBU component is most dominant in forward proton emission at the incident energies of 56 and 100 MeV. Thus, it is suggested that the NBU process makes the most dominant contribution to nucleon emission in the incident energy range below 100 MeV. Also, a characteristic step-like structure is observed in the high emission energy region, especially in TTNYs at the incident energies below 25 MeV. This high-energy component is formed by the p-TR process. Therefore, treatment of the p-TR component plays an essential role in reproducing neutron emission spectra in the high emission energy region, particularly for relatively low incident energies.

On the other hand, the DEURACS calculation underestimates the TTNY spectra in the low emission energy region. This underestimation is attributed to the absence of sequential neutron emission from unstable nuclei (e.g., ^{5}He) and discrete levels in residual light nuclei [e.g., ^{9}Be(E_x = 2.43 MeV)]. Such neutron decay is not correctly taken into consideration in the CCONE code, which is integrated in DEURACS. Thus, further improvement of the statistical model calculation in the CCONE code will be necessary as one of our future subjects.

References

[1] R. Fujita, J. Atomic Energy Soc. Jpn. **58**, 93 (2016) (in Japanese).

[2] Y. Nagai *et al.*, J. Phys. Soc. Jpn. **82**, 064201 (2013).

[3] S. Nakayama and Y. Watanabe, J. Nucl. Sci. Technol. **53**, 89 (2016).

[4] M. Yahiro, K. Ogata, T. Matsumoto, and K. Minomo, Prog. Theor. Exp. Phys. **2012**, 1A206 (2012), and references therein.

[5] T. Ye, Y. Watanabe, and K. Ogata, Phys. Rev. C **80**, 014604 (2009).

[6] T. Ye, S. Hashimoto, Y. Watanabe, K. Ogata, and M. Yahiro, Phys. Rev. C **84**, 054606 (2011).

[7] P. D. Kunz, computer code DWUCK4, http://spot.colorado.edu/kunz/DWBA.html.

[8] O. Iwamoto, J. Nucl. Sci. Technol. **44**, 687 (2007).

[9] O. Iwamoto, N. Iwamoto, S. Kunieda, F. Minato, and K. Shibata, Nucl. Data Sheets **131**, 259 (2016).

[10] S. Nakayama, H. Kouno, Y. Watanabe, O. iwamoto, and K. Ogata, Phys. Pev. C **94**, 014618 (2016).

[11] N. Otuka *et al.*, Nucl. Data Sheets **120**, 272 (2014), https://www-nds.iaea.org/exfor/exfor.htm.