Study of deuteron-induced reactions for nuclear design of accelerator neutron sources for medical application

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INTRODUCTION

In recent years, accelerator-driven neutron sources using deuteron-induced (*d,xn*) reactions on light nuclei (^{7}Li, ^{9}Be, ^{12}C, etc.) have attracted attention in various fields. Figure 1 shows experimental thick target neutron yields from (*p,xn*) and (*d,xn*) reactions on ^{9}Be [1,2]. This figure shows some advantages of a (*d,xn*) neutron source over a (*p,xn*) neutron source. First, the amount of generated neutrons is large. Second, the neutron spectrum has a broad energy peak around half the deuteron incident energy. This means that the most probable neutron energy can be changed by adjusting incident deuteron energy. In addition, the (*d,xn*) reaction has strongly forward-peaked angular distribution, which is an additional advantage from the point of view of shielding. From these favorable features, accelerator neutron sources using deuteron-induced reaction have been proposed not only for irradiation testing of fusion reactor materials [3] but also for medical purposes [4,5].

In these various applications, we pay particular attention to the generation of medical isotopes ^{64}Cu ($T_{1/2}$ = 12.7 h) with neutrons generated by C(*d,xn*) reactions [6]. To produce ^{64}Cu, it is expected that the ^{64}Zn(*n,p*) ^{64}Cu reaction with neutrons below 10 MeV will be effective. This is because Figure 2 indicates that by-products via the other reactions are expected to be suppressed in this energy range. The selectivity of the most probable neutron energy for (*d,xn*) neutron sources is useful in the case where a certain neutron energy range is required like this case.

For nuclear design of such (*d,xn*) neutron sources, comprehensive and accurate database on deuteron-induced reactions over wide ranges of target mass number and deuteron incident energy are indispensable as fundamental data. However, the number of cross section data to be stored in such database is very large. In practice, it is impossible to create it based on experimental data alone. In this case, theoretical model calculation plays an important role to complement experimental data. Therefore, we have developed a calculation code system dedicated for deuteron-induced reactions based on appropriate nuclear reaction models.

THEORETICAL MODEL

Deuteron is a very loosely bound system of proton and neutron. Thus, characteristic reaction processes on deuteron-induced reaction such as elastic breakup and stripping reaction are likely to occur. In the present study, elastic breakup and stripping reactions to continuum are calculated using the codes based on the Continuum-Discretized

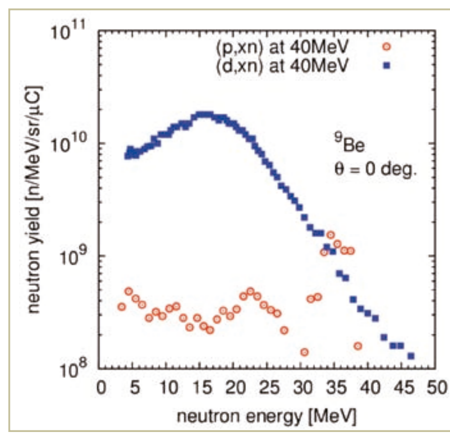

Figure 1. Thick target neutron yields from (*p,xn*) and (*d,xn*) reactions on ^{9}Be at 40 MeV. The experimental data are taken from Refs. [1,2].

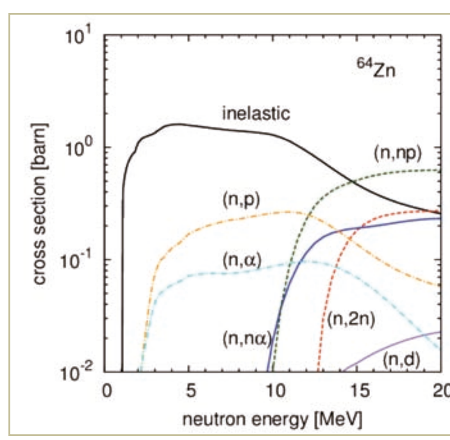

Figure 2. Neutron cross sections for ^{64}Zn taken from JENDL-4.0 [7].

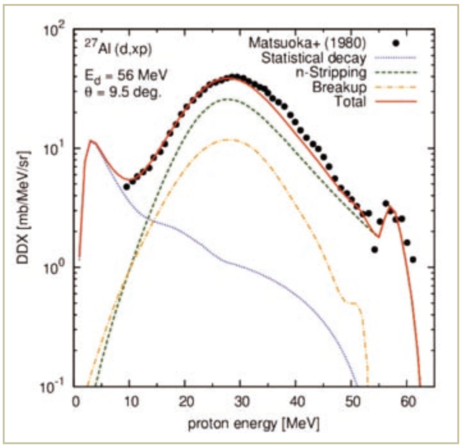

Figure 3. Calculated and experimental DDXs for ^{27}Al (*d*,*xp*) reaction at 56 MeV.

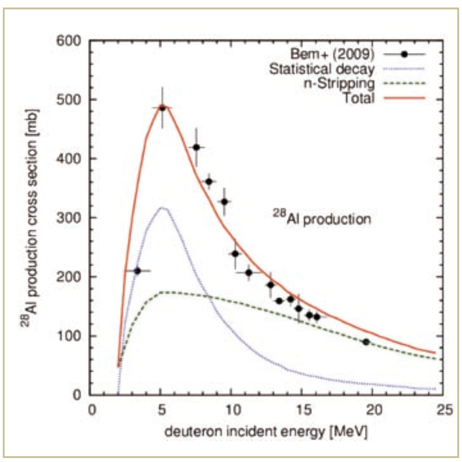

Figure 4. Calculated and experimental production cross section of ^{28}Al.

Coupled-Channels (CDCC) theory [8] and the Glauber model [9], respectively. In addition, DWUCK4 [10], which is the calculation code based on a conventional zero-range distorted wave Born approximation (DWBA) is used to calculate stripping reaction to bound states in the residual nuclei. Finally, statistical decay component from compound nuclei are calculated using the Hauser-Feshbach and exciton models implemented in CCONE code [11].

RESULTS AND DISCUSSION

Double-differential cross section

For nuclear design of neutron sources, double-differential cross sections (DDXs) for (*d*,*xn*) reactions are critically important quantity. However, experimental data of DDXs for (*d*,*xn*) reactions are lack over wide ranges of target mass number and incident energy. On the other hand, experimental data of DDXs for (*d*,*xp*) reactions do exist. To validate the employed physical models, therefore, we have compared the calculation results with experimental data about DDXs for (*d*,*xp*) reactions instead of (*d*,*xn*) reactions.

A comparison between the calculated and experimental DDXs for (*d*,*xp*) reactions on ^{27}Al at 56 MeV [12] is shown in Figure 3. The sum of each component calculated with physical models reproduces both the shape and magnitude of the experimental (*d*,*xp*) spectra including the broad peak around half the deuteron incident energy. In addition, the sharp peak observed in the high emission energy region is also reproduced well. These characteristic peaks are formed by proton emission via elastic breakup and neutron stripping processes. This indicates that it is essential to choose theoretical models to describe adequately both the breakup and stripping processes characteristic of deuteron-induced reactions.

Production cross section of ^{28}Al

It is also important to estimate production of radioactive nuclei from the viewpoint of nuclear design of deuteron accelerator neutron sources. In Figure 4, production cross sections of ^{28}Al ($T_{1/2}$ = 2.24 min) from deuteron-induced reaction on 27Al are calculated and compared with experimental data [13]. The sum of the statistical decay components and the contribution from stripping to bound states reproduce the experimental data in the low incident energy region. This result indicates the importance of considering the stripping reaction to bound states appropriately in the calculation of deuteron-induced reaction.

CONCLUSIONS

Deuteron-induced reactions are simulated by using the developed code system based on modern physical models for involved reaction processes. To validate the models, calculation results are compared with experimental data for double-differential (*d*,*xp*) cross sections on ^{27}Al and production cross sections of ^{28}Al. The results demonstrate that the reaction models used in the present calculations will be applicable to development of the database on deuteron-induced reactions necessary for nuclear design of accelerator neutron sources for medical application.

ACKNOWLEDGEMENTS

The authors wish to thank O. Iwamoto, K. Ogata, and T. Ye for their kind cooperation and fruitful discussion about theoretical model and code development.

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