Evaluation of the neutron energy spectrum, angular distribution, and yield of the ^{9}Be(d,n) reaction with a thick beryllium target

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A mathematical model and a computer program are developed to calculate the neutron energy spectrum, angular distribution, and integrated yield of the ^{9}Be(d,n) reaction on a thick beryllium target as an accelerator-based neutron source in the incident-deuteron-energy range from 0.5 to 20.0 MeV. The double-differential cross section computed by the TALYS code and the stopping power derived from the SRIM-2010 code are adopted in the program. Typical computational results are presented, and are compared with the previous experimental data to evaluate the computing model as well as the characteristics of the ^{9}Be(d,n) reaction with a thick Be target. Moreover, the developed theory and calculation methods can also provide a reasonable evaluation for calculating data of double-differential cross sections and stopping power. This model and the program can predict the above characteristics parameters of the ^{9}Be(d,n) reaction for a thick beryllium target as a neutron source in the incident-deuteron-energy range from 0.5 to 20.0 MeV.

I. INTRODUCTION

Neutron sources based on deuteron ions bombarding a light-element target play an important role in neutron physics and neutron application technology. Typical reactions include ^{2}H(d,n)^{3}He, ^{3}H(d,n)^{4}He, and ^{9}Be(d,n). The characteristics of ^{2}H(d,n)^{3}He and ^{3}H(d,n)^{4}He neutron sources, such as neutron energy spectrum, angular distribution and integrated yield, have been investigated widely due to their importance in producing monoenergetic neutrons at lower bombarding deuteron energy [1,2]. Recently, the ^{9}Be(d,n) reaction on a thick beryllium target as an accelerator-based neutron source has created interest in some potential applications, such as boron neutron capture therapy (BNCT) [3,4], radiobiology [5], and materials-damage studies [6]. In contrast with ^{2}H(d,n)^{3}He and ^{3}H(d,n)^{4}He neutron sources, which use a titanium target to adsorb deuterium or tritium gas, an accelerator-based ^{9}Be(d,n) neutron source is a good choice: the beryllium metal target, which is chemically stable, can be machined into convenient shapes, and is capable of withstanding high beam currents of mA and operating over a long lifetime due to its higher melting point (1280 °C) and better thermal conductivity.

In each of the applications [3–6] using a ^{9}Be(d,n) neutron source, detailed information on the neutron energy spectrum, angular distribution, and integrated yield is essential to analyze the experimental data accurately and to optimize the design of the shielding and collimation system. Some studies on the characteristics of the ^{9}Be(d,n) reaction neutron source with a thick Be target have been reported previously [3], [5–18]. However, many of them only presented the neutron yields at a few deuteron energies, or just measured the neutron energy spectra in a few emission angles. In this work, a mathematical method for computing the characteristics of the ^{9}Be(d,n) reaction neutron source with a thick Be target is developed

with double-differential cross section data from TALYS code. The purpose is to predict the neutron energy spectrum, angular distribution, and neutron yield in the deuteron energy range from 0.5 to 20.0 MeV, and present the results in a convenient form over wide range of emission angles. Typical calculation results are compared with previous experimental data to evaluate the computing method and TALYS code.

II. METHODS

A. Neutron energy spectrum

For the accelerator-based ^{9}Be(d,n) reaction neutron source using a thick Be target, the neutron energy spectrum can be derived as

$$\frac{dY_n^2}{d\Omega\, dE_n}(\theta, E_n, E_{dI})$$
$$= \int_{E_{dI}}^{0} I_0 N_d \frac{d^2\sigma}{d\Omega\, dE_n}(\theta, E_n, E_d)\frac{1}{S(E_d)}dE_d, \quad (1)$$

where E_{dI} and I_0 are the energy and the intensity of the incident deuteron ion, respectively. N_d is the atomic density of the Be target. θ is the neutron emission angle. E_d is the deuteron energy in the target, and E_n is the neutron energy. $\frac{d^2\sigma}{d\Omega\, dE_n}$ is the double-differential cross section of the ^{9}Be(d,xn) nuclear reaction. $S(E_d) = -\frac{dE_d}{dx}(E_d)$ is the stopping power of the deuteron in the Be target.

In order to calculate the neutron energy spectrum for the thick Be target, a thick target is divided into many thin layers. The neutron energy spectrum in each layer is given by

$$\frac{dY_{n,i}^2}{d\Omega\, dE_n}(\theta, E_n, E_{d,i})$$
$$= I_0 N_d \frac{d^2\sigma}{d\Omega\, dE_n}(\theta, E_n, E_{d,i})\frac{1}{S(E_{d,i})}\Delta E_{d,i}, \quad (2)$$
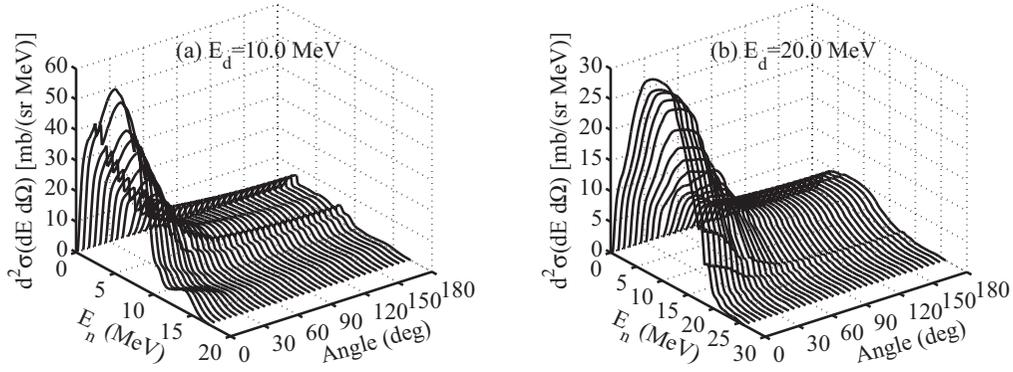
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FIG. 1. The double-differential cross sections of the ^{9}Be(d,xn) reaction using the TALYS code at incident deuteron energies of 10.0 and 20.0 MeV.

where i is the index of the layer, $E_{d,i}$ is the deuteron ion energy bombardment on the ith layer, and $\Delta E_{d,i}$ is the energy loss of deuteron ion in the ith layer. Then, the neutron energy spectrum for the thick target is obtained by

$$\frac{dY_n^2}{d\Omega \, dE_n}(\theta, E_n, E_{dI}) = \sum_i \frac{dY_{n,i}^2}{d\Omega \, dE_n}(\theta, E_n, E_{d,i}), \quad (3)$$

where $E_{d,i}$ can be approximated as the deuteron ion energy before penetrating through the ith layer. If $E_{d,0} = E_{dI}$ and $\Delta E_{d,0} = 0$, $E_{d,i}$ and $\Delta E_{d,i}$ are computed by

$$E_{d,i} = E_{d,i-1} - \Delta E_{d,i-1}, \quad (4)$$

$$\Delta E_{d,i-1} = S(E_{d,i-1})\Delta x_{i-1}, \quad (5)$$

where Δx_{i-1} is the thickness of the $(i-1)$th layer.

B. Neutron angular distribution and integrated neutron yield

On the basis of Eq. (3), the differential neutron yield in the θ emission direction, which is the neutron angular distribution data for the thick target, is represented as

$$\frac{dY_n}{d\Omega}(\theta, E_{dI}) = \int_{E_{\min}}^{E_{\max}} \frac{dY_n^2}{d\Omega \, dE_n}(\theta, E_n, E_{dI})dE_n, \quad (6)$$

where $E_{\max}$ and $E_{\min}$ are the maximum neutron energy and the minimum neutron energy, respectively. The integrated neutron yield $Y_n(E_{dI})$ in 4π solid angle is computed by

$$Y_n(E_{dI}) = 2\pi \int_0^\pi \frac{dY_n}{d\Omega}(\theta, E_{dI}) \sin(\theta)d\theta. \quad (7)$$

C. Double-differential cross section

The theory and calculation methods above show that it is possible to compute the neutron energy spectrum, angular distribution, and yield for a thick Be target if the double-differential cross section data are provided for the ^{9}Be(d,xn) nuclear reaction. For an incident deuteron ion with lower energy, ^{9}Be(d,n)^{10}B ($Q = +4.36$ MeV) is the principal reaction. The neutron energy spectrum is a continuous spectrum as there are four well known excitation states of ^{10}B [19]. For an incident deuteron ion with high energy, several

many-body reactions, such as ^{9}Be($d,2n$)^{9}B ($Q = -4.1$ MeV), ^{9}Be(d,np)^{9}Be ($Q = -2.2$ MeV), ^{9}Be($d,2np$)^{8}Be ($Q = -3.8$ MeV), etc., will lead to enhanced neutron yield and produce a broader neutron energy spectrum. For the above reasons, the experimental measurements of the cross section of the ^{9}Be(d,xn) reaction, especially for the double-differential cross section, are arduous work. Up to now, the experimental data and the recommended data of the double-differential cross section of the ^{9}Be(d,xn) reaction are still inadequate. Fortunately, a TALYS code which can be used to calculate the double-differential cross section of the ^{9}Be(d,xn) nuclear reaction has been developed by Koning *et al.* [20].

In this work, the double-differential cross section data of the ^{9}Be(d,xn) nuclear reaction are computed using the TALYS code for different incident deuteron energies. There are various nuclear reaction models including direct reaction, complex-particle pre-equilibrium, compound, and multiple in the TALYS code. A series of parameters, such as Cbreak, Cstrip, Cknock, gnadjust, M2constant, avadjust, rvadjust, and so on, need to be fixed. The above parameters are optimized to compute the neutron energy spectrum, angular distribution and yield for a thick Be target using Eqs. (3), (6), and (7), compared with the experimental data of the angular distribution and differential neutron yield at 0° emission angle of the ^{9}Be(d,n) reaction from Refs. [9,10,14]. Data based on the double-differential cross section in the deuteron energy range from 0.5 to 20.0 MeV are developed to calculate the neutron energy spectrum, angular distribution, and integrated yield of a ^{9}Be(d,n) neutron source using a thick Be target. Two examples on the double-differential cross sections are shown in Fig. 1, corresponding to 10.0 and 20.0 MeV deuteron energies and in the range from 0° to 180° with a 5° step.

D. Stopping power

Because of the lack of experimental and recommended data for the deuteron stopping power in the Be target, the computed results from the SRIM-2010 code [21] are employed in this investigation. The computational results are shown in Fig. 2. Compared with the previous experimental data of the deuteron stopping power in beryllium metal [22,23], it shows that the
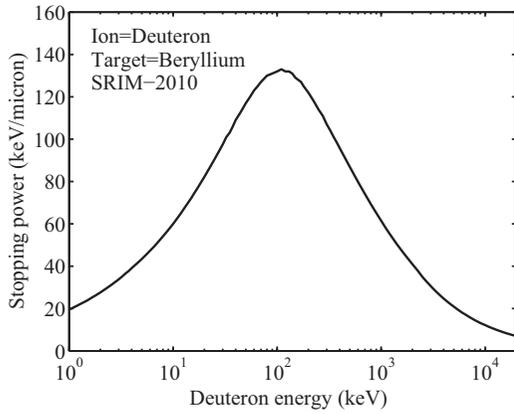
FIG. 2. The stopping power of the ^{9}Be(d,n) nuclear reaction using the SRIM-2010 code.

stopping-power data from SRIM-2010 are 11.65% lower than the experimental results by Bader *et al*. [23].

III. RESULTS AND DISCUSSIONS

A. Neutron spectrum

On the basis of the double-differential cross section produced by the TALYS code, a computer program based on the model of Eqs. (3), (6), and (7) is developed to calculate the characteristics of the ^{9}Be(d,n) reaction neutron source with the thick Be target. The program can present the neutron energy spectrum, angular distribution, and integrated neutron yield

in any emission direction under the incident-deuteron-energy range from 0.5 to 20.0 MeV.

Examples of the computed neutron energy spectrum for thick Be target are shown in Figs. 3(a)–3(d), corresponding to 7.0, 13.5, 17.0, and 20.0 MeV incident deuteron energies, respectively. Figure 3 provides the neutron energy spectra in the emission angle range from 0° to 180° with 5° intervals.

In order to evaluate the reliability of the computed data, comparisons between the computed neutron energy spectra and the previous experimental data at 0° emission angle are presented in Fig. 4. The appearance of the calculated spectra shows a better agreement with the experimental spectra in the neutron energy range greater than 2.0 MeV. In a previous investigation [10], a small peak was observed near 0.8 MeV neutron energy in every experimental spectrum. This phenomenon is considered to have a correlation with the inelastic scattering reaction of ^{9}Be(d,d')^{9}Be*. ^{9}Be* at the 2.43 MeV excited state decays to produce neutrons with an energy of 0.8 MeV, i.e., ^{9}Be(d,d')^{9}Be* → ^{8}Be + n. The difference in the neutron energy range lower than 2.0 MeV indicates that the neutrons are produced by the ^{9}Be(d,d')^{9}Be* reaction, which is not included in the TALYS code.

B. Neutron angular distribution

Examples of the computed neutron angular distribution for the thick Be target are shown in Fig. 5. Brede *et al*. [14] have measured neutron angular distribution in the emission angle range from 0° to 150°, and the incident-deuteron-energy is 13.54 MeV. There are a few experimental differential neutron yields at 0° emission direction [9–12]. In order to evaluate the reliability of the computed neutron angular distribution,
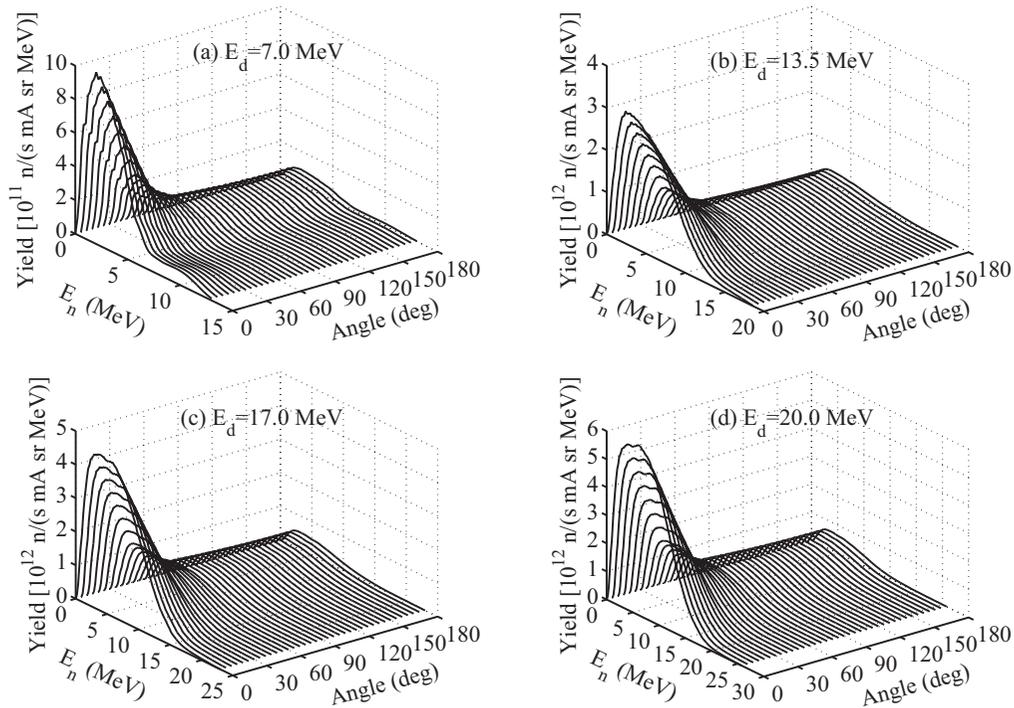

FIG. 3. Neutron energy spectra of the ^{9}Be(d,n) neutron source with the thick Be target at incident deuteron energies of 7.0 MeV (a), 13.5 MeV (b), 17.0 MeV (c), and 20.0 MeV (d).
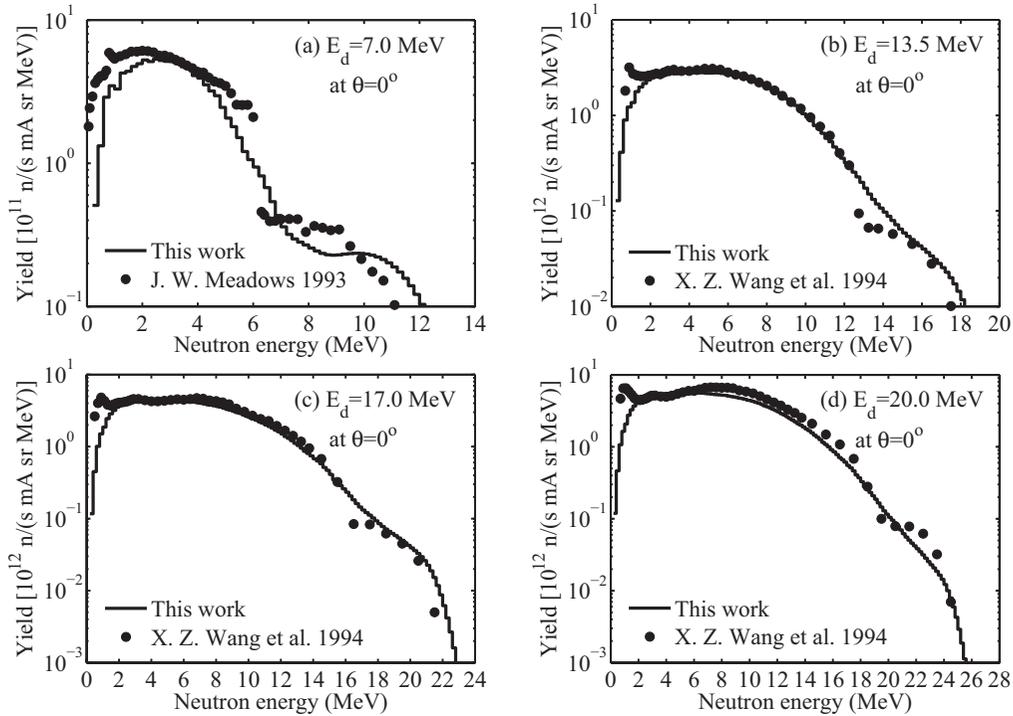
FIG. 4. Comparisons between the neutron spectra of experimental and calculated results at $\theta = 0°$.

the comparison between the computed differential neutron yields and the experimental differential neutron yields at 0° emission direction is presented in Fig. 6 for the different incident deuteron energies. Figure 6 shows a good agreement between the computed data and the experimental results.

C. Integrated neutron yield

The integrated neutron yield is an important datum for an accelerator-based neutron source, which normalizes to the beam charge, as a function of the deuteron energies. Figure 7 shows the comparison between the integrated neutron yield of the experimental [3–5,11,12,15–17] and the calculated results. They are in unanimous agreement with each other. The integrated neutron yield of a ^{2}H-Be neutron source can reach $\sim 10^{12}$ n/(mA s) for a deuteron energy of 2.0 MeV, and slowly changes along with increasing deuteron energy. The relationship between the integrated neutron yield (Y_n) and the incident deuteron energies (E_{dI}) can be described by the
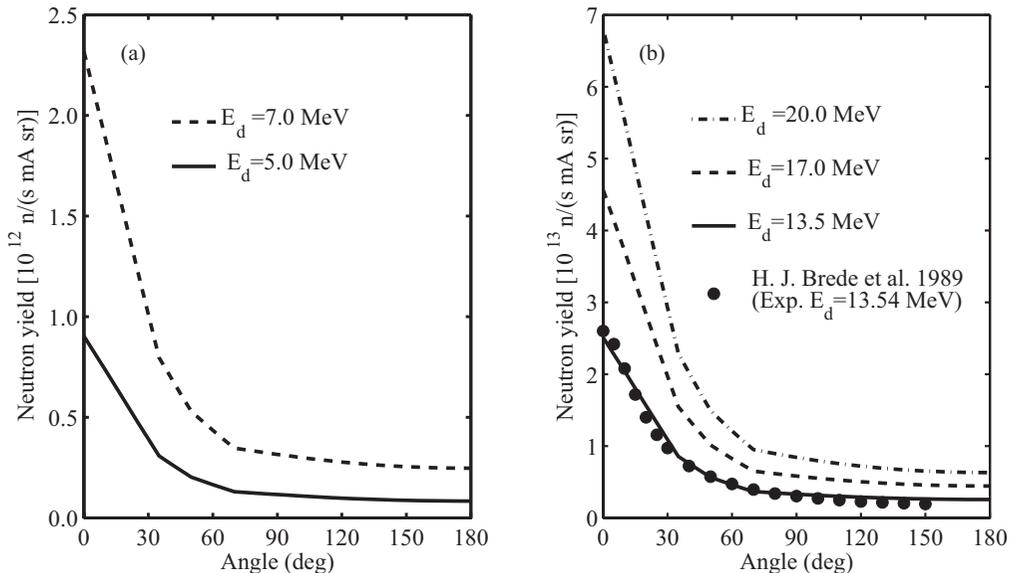

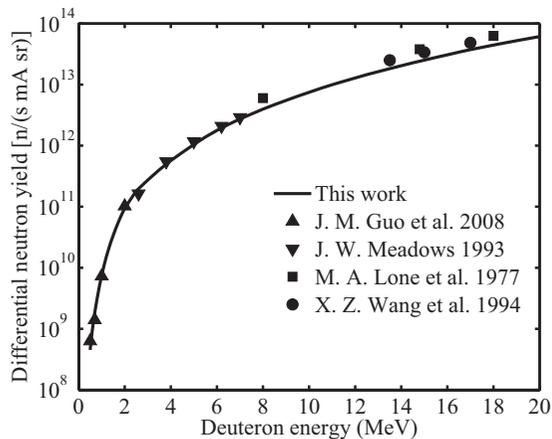FIG. 5. Neutron angular distribution of the ^{9}Be(d,n) neutron source with the thick Be target.

FIG. 6. The differential neutron yield at $\theta = 0°$ of the ^{9}Be(d,n) neutron source with the thick Be target.

FIG. 7. The integrated neutron yield of the ^{9}Be(d,n) neutron source with the thick Be target.

following equations:

$$Y_n(E_{dI})$$
$$= \begin{cases} A_1 E_{dI}^{B_1} \exp(C_1 \ln^2 E_{dI}) & (0.5 < E_{dI} \leqslant 3.0 \text{ MeV}), \\ A_2 E_{dI}^{B_2} + C_2 & (3.0 < E_{dI} \leqslant 20.0 \text{ MeV}), \end{cases}$$
(8)

where $A_1 = 1.268 \times 10^{11}$, $B_1 = 3.192$, $C_1 = -0.4193$, $A_2 = 3.232 \times 10^{11}$, $B_2 = 2.001$, and $C_2 = -3.492 \times 10^{11}$ are obtained from a least-squares fit.

IV. SUMMARY

A mathematical model and the computer program are developed to calculate the neutron energy spectra in any emission direction, angular distribution, and integrated yield of the ^{9}Be(d,n) reaction on a thick Be target as a neutron source in the incident-deuteron-energy range from 0.5 to 20.0 MeV. The computational results are in very good agreement with the experimental results.

The deviation of the calculated data relies on the thin-target approximation method, the cross section, and the stopping power data. Errors produced by the thin-target approximation method could be negligible, if the thick target is divided into thin enough layers. The relative deviation of the stopping power from the SRIM-2010 code is about 11.65% when
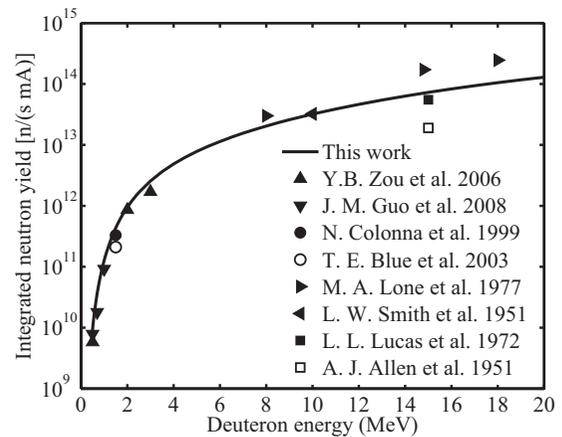
the experimental results are regarded as the benchmark. Assuming the uncertainty of the double-differential cross section is negligible, the relative deviations of the integrated neutron yield and the differential neutron yield, which will be estimated to be 11.65%, might arise mainly from the stopping power. Fortunately, such a large deviation does not produce a notable effect on the neutron energy spectrum and angular distribution. Besides, the factors of scattering, secondary reaction of ^{9}Be($n,2n$), and slowing down can all affect the actual experimental result.

Compared with the experimental data, it is found that the model and the program are capable of predicting with reasonable accuracy the neutron energy spectrum, angular distribution, and integrated yield of a ^{9}Be(d,n) reaction neutron source with a thick Be target, in the continuous energy range from 0.5 to 20.0 MeV. In addition, this study could also be an evaluation on the double-differential cross section from the TALYS code.

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