Union of Compact Accelerator-Driven Neutron Sources (UCANS) III & IV

Neutron yields of thick Be target bombarded with low energy deuterons

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Abstract

Utilization of the $^9$Be(d,n) reaction is an important option for compact accelerator-driven neutron sources, especially for low energy accelerators. It is suitable for small scale thermal or cold neutron sources. However the existing neutron yield data of the Be(d,n) reaction show large discrepancies in the low energy range. We have measured the neutron yields from thick Be target bombarded with 0.2 – 3 MeV deuterons at PKU. Here we compared our results with those from other authors. In general, Kononov’s data show the best agreement with ours. We present the total and the forward-direction neutron yields in terms of empirical formulas obtained from satisfactory fits of our data.

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Keywords: Neutron yield; $^9$Be(d,n) reaction; thick target; angular distribution.

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1. Introduction

Low energy accelerator-driven neutron sources have been developed for several decades, and the main nuclear reactions used to generate neutrons are:

\[ \text{D + d} \rightarrow \text{^{3}He + n} + 3.28 \text{ MeV} \]
\[ \text{T + d} \rightarrow \text{^{4}He + n} + 17.6 \text{ MeV} \]
\[ \text{^{7}Li + p} \rightarrow \text{^{7}Be + n} - 1.64 \text{ MeV} \]
\[ \text{^{7}Li + d} \rightarrow 2 \text{^{4}He + n} + 15.03 \text{ MeV} \]
\[ \text{^{9}Be + p} \rightarrow \text{^{9}B + n} - 1.85 \text{ MeV} \]
\[ \text{^{9}Be + d} \rightarrow \text{^{10}B + n} + 4.35 \text{ MeV} \]
\[ \text{^{9}Be + \gamma} \rightarrow 2 \text{^{4}He + n} - 1.67 \text{ MeV} \]

The corresponding thick target fast neutron yields of these reactions are showed in Fig. 1 [1].

![Fig. 1. The thick target neutron yield as a function of bombarding ion energy for various low energy nuclear reactions [1].](image-url)
At very low incidence energy (for example 200 keV) the T(d,n) reaction gives much higher neutron yield than other reactions, and at MeV energy range \(^7\text{Li}(p,n), ^7\text{Li}(d,n), ^9\text{Be}(p,n)\) and \(^9\text{Be}(d,n)\) can be chosen. Usually using \(^7\text{Li}\) as target can generate softer neutron energy spectrum than Be target, which is of benefit to moderating the fast neutrons into thermal neutrons. However to handle the Li target is much difficult than Be target, because the melt point of Li is quite low and the Li is unstable in air. So the Be target is preferable in many cases. The \(^9\text{Be}(p,n)\) reaction has a threshold above 2 MeV, so its neutron yield is higher than \(^9\text{Be}(d,n)\) only at higher energy. But the neutron energy spectrum of \(^9\text{Be}(p,n)\) is also softer than \(^9\text{Be}(d,n)\). Therefore for thermal neutron source the \(^9\text{Be}(d,n)\) reaction is suitable when incidence energy is lower than 4 MeV [2]. Even when the incidence energy is only several hundred keV, the \(^9\text{Be}(d,n)\) reaction might be considered as an option. Comparing with T(d,n) reaction, the neutron energy spectrum of \(^9\text{Be}(d,n)\) is much softer and easier to be moderated. Furthermore the Be target usually has longer lifetime than tritium target and need no special measures to prevent tritium from escaping. A main concern is the generation of neutrons from spurious reactions which may occur if some deuterons are impeded during transmission, e.g., by deposition on the surfaces on materials along the path, and then interact with other incoming deuterons via the D(d,n) reaction. This effect will obscure data collection for the Be(d,n) reaction. Therefore a good transmission of deuteron beam is important.

The fast neutron yield data are essential to design an accelerator-driven neutron source, so the neutron yield at 0\(^\circ\), the angular distribution of yield and the total neutron yield of \(^9\text{Be}(d,n)\) reaction for different deuteron energy have been measured by many scientists in the past several decades. In 1953 the yields of \(^9\text{Be}(d,n)\) reaction for deuteron energies of 400 keV, 600 keV and 800 keV were published in Segre’s book [3]. In 1967 Inada et al. measured the neutron spectra and yields at 0\(^\circ\) to 150\(^\circ\) and total yield for deuteron energies from 0.9 MeV to 2.8 MeV [4]. In 1976 Whittlestone measured the neutron spectra and yields at 0\(^\circ\) to 150\(^\circ\) and deuteron energies of 1.4, 1.8, 2.3 and 2.8 MeV as well as the total neutron yields at the four energies were derived [5]. In 1977 Hawkesworth presented a yield curve for deuteron energies from 0.3 MeV to 6 MeV [1]. In 1992 Meadows measured the yield at 0\(^\circ\) for deuteron energies between 2.6 MeV and 7.0 MeV [6]. In 1997 Guzek et al. measured the neutron yields at 0\(^\circ\) to 120\(^\circ\) for deuteron energies of 1.5 MeV [7]. In 1998 Colonna et al. measured the neutron yields at 0\(^\circ\) and the total neutron yields at deuteron energies of 1.5 MeV [8]. In 2006 Kononov measured the neutron yields at 0\(^\circ\) and the total neutron yields for deuteron energies of 0.7 – 2.2 MeV [9]. However the above neutron yield data display large discrepancies. Some data are higher than others for about three times, see Fig. 2. The possible reason might be discrimination against gamma signals was inadequate during neutron counting, or the background was not properly subtracted. Also there are fewer data points for deuteron energies below 1 MeV.

Fig. 2. The neutron yield data of \(^9\text{Be}(d,n)\) reaction published till 2006. (a) Neutron yield at 0\(^\circ\); (b) Total neutron yield.
To clarify the discrepancy among the published data sets and to add new data points at high energies, we have measured the neutron yields of thick Be target bombarded with 0.2 – 3 MeV deuterons at Peking University (PKU). Our results can be described by an expression with three parameters determined from fitting the data to the empirical formula.

2. Measurements

2.1. Method

To obtain the total neutron yield the angular distribution of the emitted neutrons should be measured, and then an integration of the partial spectral yields for different angles should be taken. There are mainly two methods to measure the neutron yield at a certain direction. One method is to measure the fast neutron energy spectrum at that direction, and then to integrate the spectrum above certain energy threshold. The neutron energy spectrum is usually measured by Time-of-Flight (TOF) method using the detectors of $^{235}\text{U}/^{238}\text{U}$ fission chamber or scintillator and phototube. Another method is to measure the angular distribution of emitted neutron directly using a neutron long counter with a BF3 proportional counter. We used the second method for our measurements. Care was taken to achieve good accuracy in the deuteron beam current data and good statistics neutron counts for an accurate neutron-yield measurement.

2.2. Experimental setup

To reduce the scattering of neutrons on target structure materials, the target structure should be as simple as possible, as long as the cooling requirement can be met. So the 1 mm thick Be target with diameter of 10 mm is cooled by water directly. The structure of target assembly is showed in Fig. 3(a). The Be target is mounted on the bottom of a Faraday cup, which is isolated from the beam tube and beam defining aperture. A bias voltage is used to suppress the secondary electrons, and a beam current integrator is used to measure the total charge accumulated.

The detector arrangement is showed in Fig. 3(b), one long counter is used to measure the yield angular distribution, and the second long counter is located at the direction of 20° to monitor the deuteron beam stability. The long counters have been calibrated, and their efficiency of fast neutron detection varied little for the neutron energy from 10 keV to several MeV. The output signal of detector is monitored by multichannel analyzer to ensure the pulse magnitude spectrum is right. The background is measured and subtracted.

Fig. 3. The experimental setup. (a) Target assembly; (b) Detector arrangement.
2.3. Facilities

The neutron yields were measured on two facilities [10-11]. The yield data for D\(^+\) energies of 1 MeV – 3 MeV were measured on 4.5 MV Van de Graaff (VDG) at Peking University. The Van de Graaff cannot be operated stably at a terminal voltage below 0.7 MV so D\(_2\)\(^+\) beam is adopted to measure the yield data of 0.5 MeV and 0.7 MeV. The neutron yield data for D\(^+\) energies of 0.2 MeV – 0.5 MeV were measured on the 600 kV Cockcroft-Walton (CCW) accelerator at China Institute of Atomic Energy (CIAE) with the same experimental setup. The neutron yield data for D\(^+\) energies of 0.5 MeV were measured on both facilities as a cross check. Later and independently, Jiang et al. from CIAE also measured the neutron yields for D\(^+\) energies of 0.1 MeV – 0.5 MeV on the 600 kV Cockcroft-Walton accelerator at CIAE using a different target assembly [12].

3. Results and discussions

3.1. Neutron yield at 0°

The neutron yields at 0° were measured for D\(^+\) energies of 0.2, 0.3, 0.4, 0.5, 0.7, 1.0, 1.5, 2.0, 2.5 and 3.0 MeV. The measurement error is about 6%, which mainly arises from the uncertainty of detector efficiency and the background subtraction. The corresponding data are showed in Fig. 4 together with the results of Jiang et al. The Jiang’s data point of 0.1 MeV is obviously too high. The uncertainty of this data point is probably very large due to the very low neutron yield.

Fig.4 indicates that our data agree well with the neutron yields given by Kononov. We fit our combined data from the two measurements using an empirical formula

\[ Y_0(E) = AE^B \exp(C \ln E^2), \]

and obtained a satisfactory description of \( A = 7.836 \times 10^6 \) n/sr/\(\mu\)C, \( B = 3.853 \), \( C = -0.288 \). The neutron yields given by Meadows, Colonna and Jiang are in good agreement with our results but the data of Inada and Guzdek fall far too high from and that of Whittlestone somewhat closer to the fitted curve (see Figure 4).

![Fig. 4. The \(^9\)Be(d, n) thick-target yield at 0°.](image-url)
3.2. Angular distribution

To obtain the total neutron yields, we use the measured angular distributions of neutron yields for six different deuteron energies 0.2, 0.5, 0.7, 1.0, 2.0 and 3.0 MeV. As showed in Fig. 5, the results indicate that the yield is almost isotropic when the deuteron energy is lower than 1 MeV. At energies higher than 2 MeV there is a tendency of high yield toward to forward direction.

![Fig. 5. Angular distributions of fast neutron produced by deuteron beam incident on a thick Be target at various bombarding energies.](image)

3.3. Total neutron yield

The total neutron yields can be derived by integrating all the observed data over the angular range. After proper normalization the result is show in Fig. 6. Comparing with the published data, those by Konomov show the best agreement with our result.

![Fig. 6. Total neutron yield versus incident deuteron energy.](image)
We use the same empirical formula to fit our combined data of the total neutron yield:

\[ Y(E) = A E^B \exp(C \ln^2 E), \]

and obtain a satisfactory description characterized by \( A = 8.943 \times 10^7 \text{n/sr}/\mu\text{C}, B = 3.376, C = -0.505 \). The neutron yields given by Colonna and Jiang agree well with our result, but the data of Inada, Whittlestone and Segre are too high. The curve of Hawkesworth agrees with ours only at high energy (> 2MeV), otherwise showing higher values than ours at low energies.

4. Conclusions

The neutron yields of Be(d,n) reaction for deuteron energies of 0.2 – 3 MeV have been measured at PKU. Our new data covering a wide energy range delineate more clearly the discrepancies among the previously published data. The overall yield of Be(d,n) represented by an empirical formula is useful for the design of compact accelerator-driven neutron sources. The corresponding data are useful to design a compact accelerator-driven neutron source using such a reaction.

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