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Neutron spectrum determination of d(20)+Be source reaction by the dosimetry foils method

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ABSTRACT

The cyclotron-based fast neutron generator with the thick beryllium target operated at the NPI Rez Fast Neutron Facility is primarily designed for the fast neutron production in the p+Be source reaction at 35 MeV. Besides the proton beam, the isochronous cyclotron U-120M at the NPI provides the deuterons in the energy range of 10–20 MeV. The experiments for neutron field investigation from the deuteron bombardment of thick beryllium target at 20 MeV were performed just recently. For the neutron spectrum measurement of the d(20)+Be source reaction, the dosimetry foils activation method was utilized. Neutron spectrum reconstruction from resulting reaction rates was performed using the SAND-II unfolding code and neutron cross-sections from the EAF-2010 nuclear data library. Obtained high-flux white neutron field from the d(20)+Be source is useful for the intensive irradiation experiments and cross-section data validation.

1. Introduction

The accelerator driven fast neutron sources with broad neutron spectra are mostly built on thick beryllium targets, because the deuteron induced (d+Be) and proton induced (p+Be) source reactions on beryllium target have the increasing value of cross-sections for neutron production in the energy range from several MeV to tens of MeV and thus the high value of the neutron spectral yield. The melting point of the beryllium has a value of 1 287 °C (Chu et al., 2016), so it is possible to use the charged particle beams of high intensity. One of the most important issues connected with beryllium as a target material is its high toxicity (Petzow et al., 2005).

The NG-2 accelerator driven fast neutron generator with beryllium target station operated at the Nuclear Physics Institute (NPI) of The Czech Academy of Sciences (CAS) uses the proton beam delivered by the isochronous cyclotron U-120M for the high-energy neutron field production up to 34 MeV. This neutron field is used in the irradiation experiments carried out within the fusion related research applications (e.g. IFMIF research program – International Fusion Material Irradiation Facility (Mollendorf et al., 2002)). However, the neutron field produced in deuteron bombardment of the beryllium and suitable for the intensive irradiation experiments up to 20 MeV was recently studied in close vicinity from the source target, and obtained results are presented in this paper.

2. Materials and methods

2.1. The d+Be neutron source reaction

The d+Be source interaction was intensively investigated by several scientists in the 70s and 80s of the last century. Neutron spectra were experimentally studied by Lone et al. (1977), (Meulders et al., 1975), Weaver et al. (1973); Graves et al. (1979); Brede et al. (1989); Saltmarsh et al. (1977); Meadows et al. (1993); Waterman et al. (1979), and Madey et al. (1977). It was found (especially from Lone's and Meulders' measurements) that for deuteron beam energy E_d above 10 MeV, the mean energy of neutron spectrum $\overline{E}_n$ above 2 MeV in the forward direction can be described by the following empirical equation (Lone et al., 1977; Meulders et al., 1975; Cierjacks, 1983):

$$\overline{E}_n = 0.4 \times E_d - 0.3 \qquad E_d > 10\text{MeV}, \tag{1}$$

For 20 MeV deuteron beam, the fluence averaged neutron energy should be 7.7 MeV.

The main neutron producing reactions when beryllium target is bombarded by deuteron beam are summarized in Table 1. The (d,n) deuteron stripping process on beryllium is the most important neutron producing reaction; it has a Q-value of 4.4 MeV (Q-value Calculator, 2016), and it is responsible for the high energy part of neutron energy spectrum ($E_n > 0.8 \times E_d$) (Allisy et al., 1989). For a thick target, the Gaussian-like broad maximum around fourty percent of the deuteron

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Table 1
Neutron producing reactions on beryllium target bombarded by deuteron beam. (Cierjacks, 1983, Q-value Calculator, 2016).

Reaction	Q (MeV)	E_{thresh} (MeV)
^{9}Be(d,n)^{10}B	+4.36	0.00
^{9}Be(d,pn)^{9}Be	−2.22	2.71
^{9}Be(d,p2n)^{8}Be	−3.89	4.76
^{9}Be(d,p)2^{5}He *	−5.27	6.44
^{9}Be(d,^{5}He)^{6}Li	−0.83	1.02
^{9}Be(d,2n)^{9}B	−4.07	4.99

energy is formed by the multi-body break-up interactions of ^{9}Be(d,pn)^{9}Be, ^{9}Be(d,p2n)^{8}Be, ^{9}Be(d,^{5}He)^{6}Li, and ^{9}Be(d,p)2^{5}He * with subsequent ^{5}He break-up to neutron and α-particle (Saltmarsh et al., 1977; Cierjacks, 1983). The inelastic deuteron scattering on beryllium and ^{9}Be(d,2 n)^{9}B and ^{9}Be(d,pn)^{9}Be reactions create the low energy fraction of spectrum below 2 MeV as well as they form the peak at a energy of 800 keV (Allisy et al., 1989); this underlying continuum starts at very low neutron energies and falls off almost exponentially with the energy (Cierjacks, 1983).

The d+Be interaction provides the best neutron source presently available for radiotherapy when accelerators with energies of at least 15 MeV are used (Wyckoff et al., 1976). So, the typical utilization of the fast neutron spectra from beryllium targets is for neutron radiotherapy, study of radiation damage of materials, and radiation hardness of electronics against the fast neutron fields. The spectra are also used for integral benchmarks and validation of nuclear data and as the reference spectra in nuclear data libraries. Typically, from beryllium target the broad (or white) neutron spectrum is obtained and oriented in forward direction as the deuteron energy increases.

The experimentally found shapes of neutron spectra from the d+Be source reaction are depicted in Fig. 1 and 2. In Fig. 1, the spectra measured by M.A. Lone are displayed, the time-of-flight (TOF) method was utilized. In Fig. 2, the neutron spectral flux reported by J.P. Meulders for three energies is depicted; his measurement was performed by the NE-111 scintillation probe 3.

2.2. Beryllium target station NG-2

Since 2012, the beryllium target station of the NG-2 neutron generator at the NPI in Rez near Prague has been standardly operated together with the source reaction of the p+Be and for a proton beam energy up to 35 MeV. The beryllium target has a thickness of 8 mm and diameter of 5 cm, and during the operation, it is cooled by ethanol to the temperature of 5 °C. The beam power is about 420 W. The proton

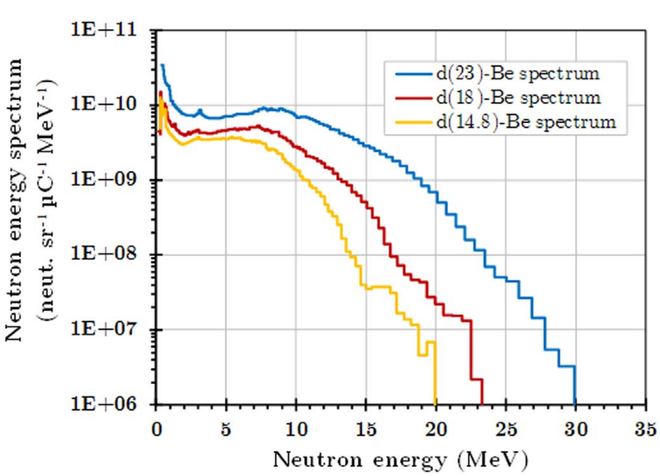

Fig. 1. The d+Be neutron energy spectra measured by Lone using TOF technique for deuteron beam energy of 14.8 MeV, 18 MeV, and 23 MeV. (Lone et al., 1977).

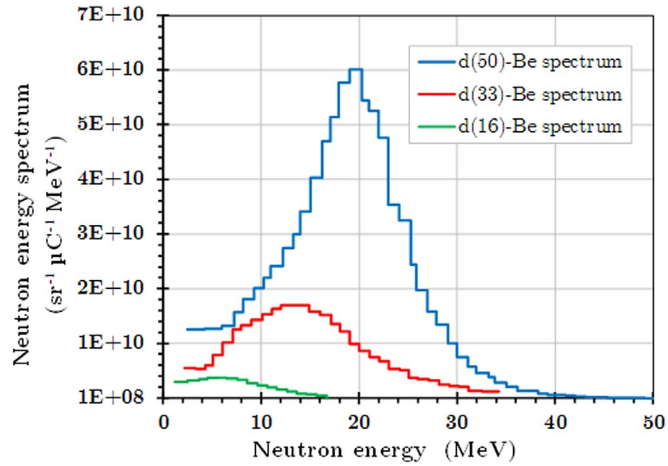

Fig. 2. The d+Be neutron energy spectra measured by Meulders using NE-111 scintillation probe for deuteron beam energy of 16 MeV, 33 MeV, and 50 MeV (Meulders et al., 1975).

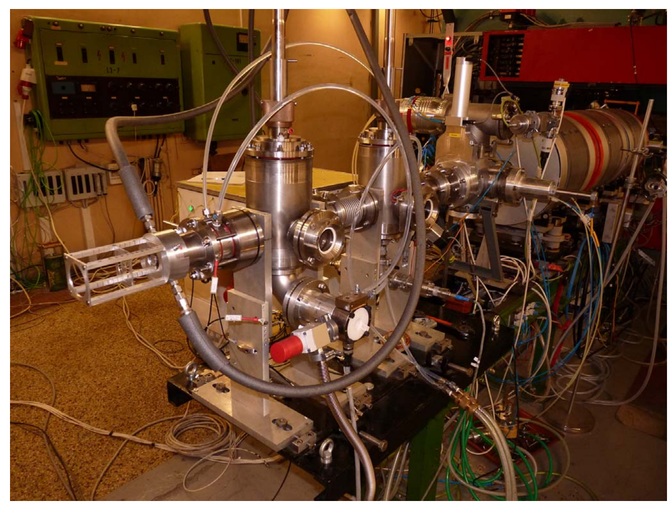

Fig. 3. Beryllium target station of the NG-2 neutron generator at the NPI with aluminium holder of activation foils.

beam current on the target and both carbon collimators, temperature, pressure, and flow rate of cooling ethanol are online monitored and registered during the experiments. In the standard operation, the beryllium target station produces the white spectrum up to 34 MeV with neutron spectral yield up to 10^{11} cm^{-2}s^{-1} in the close distance from the source target. The obtained neutron spectrum of the p(35)+Be source reaction was reported Stefanik et al. (2014b), and the spectral characteristics were analyzed Stefanik et al. (2014a) in detail. However, new experiment with deuteron beam we performed recently at the NPI. For this white neutron source based on the d+Be source reaction, the maximum deuteron energy (20 MeV) provided by the U-120M cyclotron was utilized.

2.3. Multi-foil activation technique

For the neutron field spectrometry in the irradiation system where the source-to-sample distances are short and the dimensions of production target and foils are comparable, the multi-foil activation technique is the most appropriate method. This method uses a set of dosimetry foils of various materials for measurement of responses to the neutron spectrum, i.e. the reaction rates. Afterwards, the neutron spectrum is reconstructed by the unfolding code (e.g. SAND-II) using the reaction rates determined by means of the γ-ray spectrometry, activation cross-sections, and initial guess neutron spectrum. At the