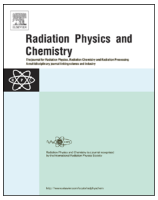
Radiation Physics and Chemistry 104 (2014) 306–309

Contents lists available at ScienceDirect

Radiation Physics and Chemistry

journal homepage: www.elsevier.com/locate/radphyschem



High-flux white neutron source based on p(35)-Be reactions for activation experiments at NPI

Milan Stefanik [a,b,*], Pavel Bem [a], Miloslav Gotz [a], Karel Katovsky [c], Mitja Majerle [a], Jan Novak [a], Eva Simeckova [a]

[a] *Nuclear Physics Institute of The Academy of Sciences of the Czech Republic, pri, Rez 130, Rez 250 68, Czech Republic*
[b] *Czech Technical University in Prague, Faculty of Nuclear Sciences and Physical Engineering, Brehova 7, Prague 115 19, Czech Republic*
[c] *Brno University of Technology, Faculty of Electrical Engineering and Communication, Technicka 10, Brno 616 00, Czech Republic*

HIGHLIGHTS

- Development of accelerator-driven neutron sources.
- Fast neutron spectrometry.
- Multi-foil activation technique.
- Nuclear data measurement and validation in the energy range of IFMIF.

ARTICLE INFO

Article history:
Received 24 June 2013
Accepted 12 June 2014
Available online 30 June 2014

Keywords:
Neutron generator
Accelerator
Dosimetry foils activation method
Neutron spectrometry
Gamma-spectrometry
Reaction rate

ABSTRACT

The concept of International Fusion Material Irradiation Facility (IFMIF) is based on the d(40)-Li neutron source reaction which produces the white neutron spectrum with mean energy of 14 MeV, energy range with high intensity of neutron beam up to 35 MeV, and weak tail up to 55 MeV. At the Nuclear Physics Institute of the ASCR in Rez near Prague, the source reaction of p+Be was investigated for proton energy of 35 MeV and beam current intensity of 9.2 μA. The produced white spectrum with neutron flux up to $10^{11}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ was determined by the dosimetry foils activation technique at two sample-to-target distances and validated against the Monte Carlo predictions. The neutron field of these high-flux p(35)-Be white neutron source represents the useful tool for experimental simulation of the spectrum of the IFMIF facility, validating the activation cross-section data in the energy range relevant to the IFMIF, studying the radiation hardness of electronics against the high-energy neutron fields, and various activation experiments.

1. Introduction

For neutron source reactions investigated at the Department of Nuclear Reactions of the NPI Rez over the past 15 years, the cyclotron based fast neutron generators of the white- and quasi-monoenergetic spectra were developed and are operated at the department utilizing the variable-energy proton beam (up to 37 MeV) and the D_2O (flow), Be (thick), and ^{7}Li(C) target stations (Bem et al., 2007). The intensity and the energy range of the produced neutron fields are suitable for the integral and differential validations of the neutron cross-sections within the ADTT (Accelerator Driven Transmutation Technology) and fusion-relevant (IFMIF – International Fusion Material Irradiation Facility) research programs.

Due to the intensity reason, the irradiated samples are usually fixed in the vicinity of the source target in the neutron activation experiments, and the dimensions of the target and samples are comparable with the target-to-sample distance. The spectral yield measured at large distance of detector from the neutron source target in point-like-geometry is not sufficient to determine the spectral flux at the sample position because of the space integration effect of neutron yield in short distances. Due to a lack of differential yield data at requested energy and angular range, the MCNPX calculations need to be validated against the independent experiments. Recently, the dosimetry-foils activation method was successfully used for the validation of the MCNPX prediction of spectral flux characteristics for the p-D_2O (thick) reaction (Simakov et al., 2007; Stefanik et al., 2012). In the present work, this method was employed to determine the spectra of the Be(p,*x*n) source reaction at the positions of irradiated samples.

---

[*] Corresponding author.
E-mail address: milan.stefanik@fjfi.cvut.cz (M. Stefanik).

http://dx.doi.org/10.1016/j.radphyschem.2014.06.009
0969-806X/

2. Neutron activation method, reaction rate

To determine the spectral flux at the position of irradiated samples, the standard multi-foil activation method is utilized. It makes possible to reconstruct the neutron spectrum by using the γ-activities of radionuclides produced by the activation reactions in a set of activation foils irradiated in this field. The result of activation measurements is the *reaction rate* per one target nuclei (s^{-1}), and is defined as

$$P_R = \frac{S_\gamma \lambda \frac{t_{real}}{t_{live}}}{N_0 \varepsilon_\gamma I_\gamma (1 - e^{-\lambda t_{irr}}) e^{-\lambda t_{cool}} (1 - e^{-\lambda t_{real}}) \eta_B} \quad (1)$$

where λ is the decay constant of radionuclide, S_γ the area under the full energy peak, N_0 the number of target nuclei in the foil, ε_γ the detection efficiency, I_γ the intensity per decay, t_{irr} and t_{cool} the irradiation and the cooling time respectively, t_{real} and t_{live} the real and the live time of the spectroscopic measurement respectively, and η_B the correction for beam fluctuation. Reaction rate is proportional to neutron flux ϕ ($cm^{-2}\ s^{-1}\ MeV^{-1}$) since

$$P_R = \int_{E_{thresh}}^{E_p + Q} \sigma(E_n) \phi(E_n)\, dE_n \quad (2)$$

where σ is the microscopic activation cross-section, E_{thresh} the energy threshold of the reaction, E_p the proton beam energy, and Q the value of reaction energy.

3. Materials and methods

3.1. Beryllium target station NG-2

The powerful fast neutron sources usually provide the intense neutron beams from proton or deuteron bombardment of thick beryllium target. The beryllium target station of the NPI (Fig. 1) was build up on the beam line of the isochronous cyclotron U-120M operated in the negative-ion mode of acceleration. In this mode, the high proton beam power (320 W for 35 MeV) and the good beam-current stability present the suitable basis for irradiation experiments. During the operation, the beryllium target, with thickness of 8 mm and diameter of 50 mm, is cooled by the ethanol to the temperature of 5 °C; the proton beam current, temperature and pressure of cooling alcohol are monitored, digitized, and registered by the PC. The target cell together with the cooling and driving systems is insulated from the earth.

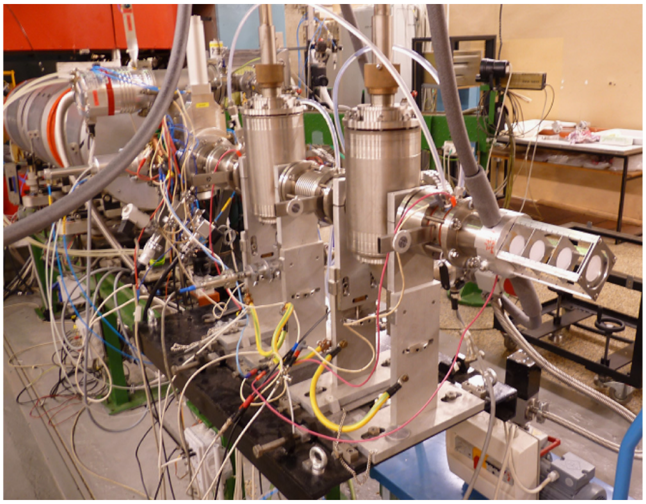


Fig. 1. Beryllium target station of the NG-2 neutron generator at the NPI with aluminum holder of activation foils.

In the standard operation, the beryllium target station produces the white spectrum with a spectral yield of 1.2×10^{11} n sr^{-1} in forward direction for proton energy up to 20 MeV. However, the high energy and high intensity p(35)-Be white neutron field for activation experiments has been developed recently, and it represents the powerful tool for neutronic tests in the energy range relevant to the IFMIF.

3.2. The p-Be neutron source reaction

During the bombardment of the beryllium target by protons at energy $E_p = 35$ MeV, the high energy neutron spectrum component is mostly produced in the ^{9}Be(p,n)^{9}B reaction to the ground state ($Q = -1.85$ MeV) and partially to highly excited states (2.3 MeV, 1.4 MeV), and the low energy spectrum component is produced in the three body break-up processes. The structure of the low energy spectrum is mainly formed by the reactions of ^{9}Be (p,np)^{8}Be ($Q = -1.67$ MeV), ^{9}Be(p,nα)^{5}Li ($Q = -3.54$ MeV), and ^{9}Be (p,pα)^{5}He ($Q = -2.67$ MeV) with subsequent ^{5}Li break-up to neutron and α-particle ($Q = 0.89$ MeV).

Fig. 2 shows the MCNPX calculated neutron spectra in dependence on various thicknesses of the beryllium target. The neutron spectrum of the thin target (0.25 mm and 0.5 mm) is produced almost by monoenergetic protons and consists of well distinguishable peaks of neutrons from the ^{9}Be(p,n)^{9}B reaction to the ground and excited states. By increasing the target thickness, the proton beam degrades by ionizing effects in the target and induces the neutron production reactions at lower energies. Due to this effect, the spectrum changes the shape from the semi-monoenergetic peak to the broad continuous spectrum.

3.3. Neutron field measurement

The current research program at the NPI requires the usage of the high energy neutron field above 20 MeV, and therefore the operation of the Be-target station was successfully tested at a proton energy of 35 MeV (beam current of 9.26 μA), i.e. nearly maximum energy provided by the cyclotron U-120M. The novel p(35)-Be neutron field was developed by utilization of the multi-foil activation method.

For neutron spectrum determination at two irradiation positions (15 and 156 mm), the set of 12 activation foils (Al, Nb, Sc, Y, MnNi, Co, In, Lu, Au, Ti, Fe, Bi) was used. The induced γ-ray activities of irradiated foils were investigated by the nuclear γ-spectrometry technique (see Table 1). The activation detectors were measured repeatedly by the semiconductor HPGe detector after various cooling time periods. The evaluation of γ-spectra was

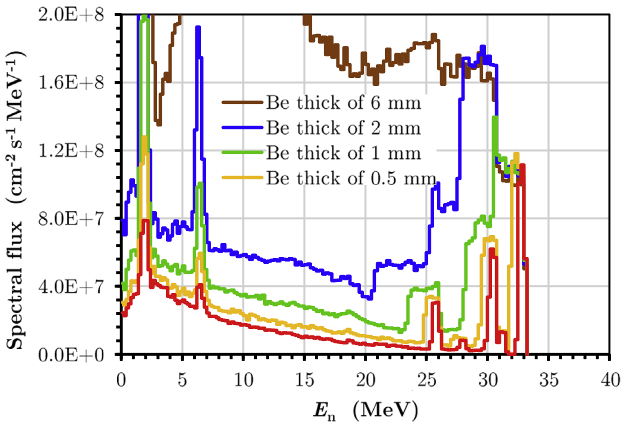


Fig. 2. The MCNPX calculated p(35)-Be neutron spectra for various thicknesses of bare beryllium target without backing.