SPECTROMETRY OF NEUTRON FIELD BASED ON P(20)+BE SOURCE REACTION

Ján Kozic[a, b, *], Milan Štefánik[a, b]

[a] *Czech Technical University in Prague, Faculty of Nuclear Sciences and Physical Engineering, Department of Nuclear Reactors, V Holešovičkách 2, 180 00 Prague 8, Czech Republic*

[b] *Nuclear Physics Institute of The Czech Academy of Sciences p.r.i., Řež No. 130, 250 68 Řež, Czech Republic*

[*] corresponding author: `kozic@ujf.cas.cz`

ABSTRACT. The research deals with a spectrometry of neutron field based on the p(20)+Be source reaction. The p(20)+Be interaction stands for a nuclear reaction where protons accelerated to energy of 20 MeV bombard Be target. Produced neutron field has broad energy distribution up to 18 MeV. The research was carried out at the Nuclear Physics Institute of the Czech Academy of Sciences and was motivated by extension of experimental possibilities of the NG-2 target station. To determine the neutron spectrum, the activation foil technique was used. During the experiment, ten activation foils were irradiated. Activated foils were measured using the HPGe detector to determine the reaction rates of observed reactions. The neutron field was simulated in the MCNPX code, and the simulation served as a priori information for the unfolding of the neutron spectrum in the SAND-II code. A determined neutron spectrum is essential for various experiments, e.g., material research, measurements of nuclear data, etc.

KEYWORDS: Accelerator-driven neutron source, beryllium target station NG-2, activation foil technique, neutron energy spectrum, SAND-II.

1. INTRODUCTION

Fusion reactors such as ITER [1], DEMO [2], are expected to use a d+T reaction which produces neutrons with energy distribution up to 20 MeV and with a peak at an energy of 14 MeV. The p(20)+Be source reaction presented in this paper produces a neutron field with a broad energy spectrum up to 18 MeV which covers almost the whole energy range of the d+T reaction. This fact allows the usage of the neutron field produced by the p(20)+Be source reaction for the material research for future fusion reactors. The new neutron field from the p(20)+Be source reaction can also be used for experiments of measurements, benchmarks of nuclear data and fast neutron activation analysis which extends experimental possibilities of beryllium target station NG-2.

2. MATERIALS AND METHODS

2.1. ACTIVATION FOIL TECHNIQUE

An activation foil technique is a method which is used to characterize an energy spectrum of neutron sources. To determine a neutron spectrum using this method a set of spectroscopically thin foils or wires are irradiated in an unknown neutron field. The foils or the wires mentioned are called activation detectors. Reactions of neutrons with the activation detectors produce radioactive nuclei which emit gamma radiation. The gamma radiation is detected using, for example, a HPGe detector. From the measurements of the gamma-ray spectra of the irradiated activation detectors, it is possible to determine the reaction rates

per target nucleus of the observed reactions using an equation

$$R_{\mathrm{R}} = \frac{\lambda S(E_\gamma)\frac{t_{\mathrm{real}}}{t_{\mathrm{live}}}}{I(E_\gamma)\varepsilon(E_\gamma)N_0(1-e^{-\lambda t_{\mathrm{irr}}})e^{-\lambda t_{\mathrm{cool}}}(1-e^{-\lambda t_{\mathrm{real}}})}, \quad (1)$$

where λ is a decay constant of the produced radioactive nucleus, $S(E_\gamma)$ is an area of a full energy gamma-ray peak, t_{live} is a duration of the measurement of gamma spectrum, t_{real} is a duration of the measurement of gamma spectrum with consideration of a dead time, $I(E_\gamma)$ is an intensity of the gamma ray, $\varepsilon(E_\gamma)$ is a detection efficiency of the apparatus for a given gamma-ray energy, N_0 is the number of target nuclei, t_{irr} and t_{cool} is an irradiation and a cooling time respectively. Correction factors are also applied. A relative uncertainty of the reaction rate is determined by an equation [5]

$$\delta_{R_{\mathrm{R}}} = \sqrt{\left(0.03\left(\frac{t_{\mathrm{real}}}{t_{\mathrm{live}}}-1\right)\right)^2 + (t_{\mathrm{cool}}\lambda\delta_{T_{1/2}})^2 + \delta_{S(E_\gamma)}^2 + \delta_{I(E_\gamma)}^2}, \quad (2)$$

where δ_j is a relative uncertainty of j-th quantity.

The reaction rate is defined by an equation

$$R_{\mathrm{R}} = \int_0^{+\infty} \phi(E_{\mathrm{n}})\sigma(E_{\mathrm{n}})\mathrm{d}E_{\mathrm{n}}, \quad (3)$$

where $\phi(E_{\mathrm{n}})$ is a neutron spectral flux density, $\sigma(E_{\mathrm{n}})$ is a microscopic cross-section of respective reaction and E_{n} is an energy of neutron. From the measurement of the irradiated activation detectors, a set of reaction rates for the observed reactions is obtained

Reaction	Energy of reaction [MeV]	Threshold energy [MeV]
$^9\text{Be(p,n)}^9\text{B}$	-1.85	2.06
$^9\text{Be(p,pn)}^8\text{Be}$	-1.66	1.85
$^9\text{Be(p,n}\alpha)^5\text{Li}$	-3.54	3.93
$^9\text{Be(p,p}\alpha)^5\text{He}^* \to \alpha+\text{n}$	-2.31	2.57
$^9\text{Be(p,np}\alpha)^4\text{He}$	-1.57	1.75
$^9\text{Be(p,}\alpha)^6\text{Li}^* \to \text{p}+\alpha+\text{n}$	-2.19	2.31
$^9\text{Be(p,}\alpha)^6\text{Li}^* \to \text{p}+^5\text{He}^* \to \text{p}+\alpha+\text{n}$	-3.25	3.61
$^9\text{Be(p,}\alpha)^6\text{Li}^* \to {}^5\text{Li}+\text{n}$	-3.53	3.92
$^9\text{Be(p,p')}^9\text{Be}^* \to \alpha+^5\text{He}^* \to \alpha+\text{n}$	-2.46	2.74

TABLE 1. Reactions of protons with beryllium which produce neutrons [3, 4].

and a process of unfolding the unknown neutron energy spectrum is based on a solution of equations resulting from the definition of the reaction rate.

2.2. P+BE AS A NEUTRON SOURCE REACTION

Based on the suitable physical properties of beryllium, mainly a melting point of 1287 °C [6] and thermal conductivity of 190 Wm^{-1}K^{-1} [6], it is possible to use it as an accelerator-driven external neutron source target, despite its toxicity [7]. Reactions of protons with beryllium which produce neutrons are summarized in Table 1. The most important neutron producing reaction is $^9\text{Be(p,n)}^9\text{B}$ which contributes to the fast component of the neutron energy spectrum. The energy of this reaction is -1.85 MeV [3], and it has threshold energy equal to 2.06 MeV [3]. The rest of the reactions listed in Table 1 produce neutrons with energy of the order of MeV units.

Depending on the beryllium target's energy thickness, the external neutron source can produce a white or semi-monoenergetic spectrum. Neutron field with white energy spectrum is a neutron field with broad energy distribution. Although the beryllium target is mostly used as an energetically thick white neutron source, Uwamino et al. [8] have studied an energetically thin beryllium target as a semi-monoenergetic neutron source. The energetically thick accelerator-driven beryllium neutron source has been intensively studied by Lone et al. [9] and Brede et al. [10]. Experimental data measured by Lone et al. and Brede et al. are shown in Figures 1 and 2 respectively. Brede et al. derived an empirical equation for the determination of a fluence averaged neutron energy [10]

$$\overline{E}_\text{n} = 0.433E_\text{p} - 1.39, \qquad (4)$$

where $\overline{E}_\text{n}$ is the fluence averaged neutron energy and E_p is an energy of incident protons. The equation is usable for neutrons with an energy higher than 2 MeV.

2.3. EXPERIMENTAL APPARATUS

At the Nuclear Physics Institute of The Czech Academy of Sciences (NPI CAS) an isochronous cyclotron U-120M and neutron target stations NG-2 are
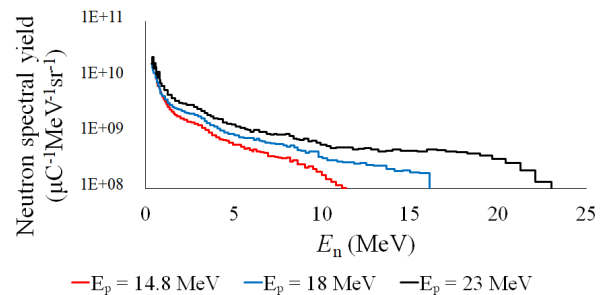

FIGURE 1. Neutron energy spectra from the source reaction p+Be measured by Lone et al. for proton energies of 14.8 MeV, 18 MeV and 23 MeV [9, 11].
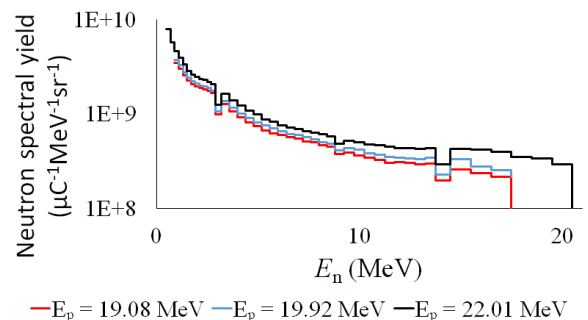

FIGURE 2. Neutron energy spectra from the source reaction p+Be measured by Brede et al. for proton energies of 19.08 MeV, 19.92 MeV and 22.01 MeV [10, 11].

operated. The cyclotron U-120M is a multi-purpose device which can accelerate the positive and negative ions. It was manufactured at the Joint Institute for Nuclear Research in Dubna Russia. At the beginning of the operation, the cyclotron was able to accelerate only positive ions. An option to accelerate negative ions was added during a modernization of the cyclotron between 1996 and 1998. The beam of accelerated ions could be extracted to a hall where the cyclotron is located or to an external experimental hall. Parameters of the ion beams extracted from isochronous cyclotron U-120M are listed in Table 2.

The Department of Nuclear Reactions of the NPI CAS operates two accelerator-driven neutron producing target stations NG-2. One of them has embedded

Ion	Energy [MeV]	Maximal current [μA]
H^+	$6-25$	5
D^+	$12-20$	5
$^3He^{+2}$	$18-52$	2
$^4He^{+2}$	$24-38$	5
H^-	$6-35$	13
D^-	$11-20$	10

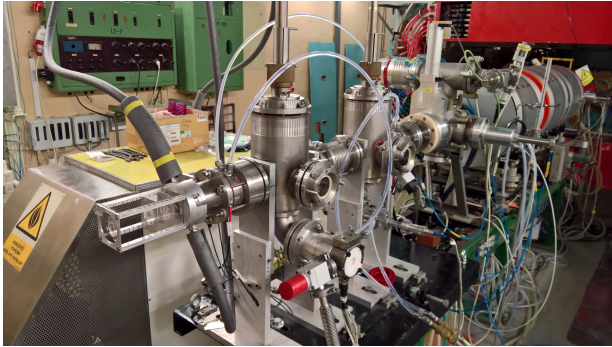TABLE 2. Parameters of the extracted ions from the cyclotron U-120M [12].

FIGURE 3. The beryllium target station NG-2 at the Nuclear Physics Institute of The Czech Academy of Sciences.

an energetically thin lithium target and the other has an energetically thick beryllium target. The beryllium target has dimensions of 8 mm in thickness and 50 mm in diameter. Because the beam of protons is fully stopped inside the beryllium target, cooling of the target is needed and it is cooled by liquid alcohol at a temperature of 5 °C. This target is used to produce a neutron field with broad energy distribution. The beryllium target station NG-2 is shown in Figure 3.

2.4. DATA ACQUISITION

To determine an energy spectrum at a position P14 (see Figure 4) of the neutron field produced by an accelerator-driven external neutron source based on a source reaction p(20)+Be, an irradiation experiment has been carried out at the Nuclear Physics Institute of The Czech Academy of Sciences. The experimental arrangement is illustrated in Figure 4. The activation foil technique has been used and a set of various high purity metallic spectroscopic foils, which has been delivered by GoodFellow Company, have been irradiated. The set of foils has contained materials Au, In, Fe, Al, Lu, Y, Co, Ti, Nb, and Ni (see Figure 5). During the experiment, the proton beam has been accelerated to the kinetic energy of 20.134 MeV and a mean current on the surface of the beryllium target has been 12.3 μA. The irradiation lasted for 11 hours. After the irradiation has ended, the activation detectors have been transferred to a gamma spectrometric
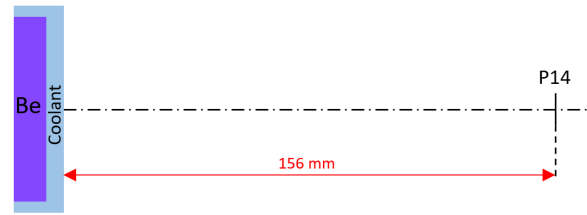

FIGURE 4. A schematic of the experimental arrangement.

FIGURE 5. The set of activation detectors.

laboratory where their gamma spectra have been measured on a HPGe Canberra semiconductor detector for four weeks.

3. RESULTS

From the measured gamma-ray spectra of the irradiated set of activation detectors the necessary quantities for determination of reaction rates of the observed reactions, which have been identified based on characteristic gamma-ray energy, a half-life of their products and with respect to their activation cross-section, have been obtained. Using Equations (1) and (2), a set of reaction rates and their relative uncertainties for the observed reactions, which are summarized in Table 3, have been determined. The reaction (n,x) denotes a combination of reactions for the natural atomic abundance of the element. A priori information about the neutron spectrum has been obtained from simulation in MCNPX v.2.7.0. code [13] using LA-150h [13] and ENDF/B-VII.1 [14] nuclear data libraries. The geometry in the simulation has been the same as has been shown in the schematic in Figure 4. The neutron energy spectrum has been successfully unfolded in SAND II code [15, 16]. During the unfolding process, 22 out of a total of 24 reaction rates have been successfully used with respective cross-sections from the EAF-2010 nuclear database [17], and the neutron energy spectrum obtained from the simulation in the MCNPX code has served as an initial guess spectrum. The unfolded neutron energy spectrum shows good agreement with the MCNPX predictions. Both simulated and unfolded neutron energy spectra from the source reaction p(20)+Be at the position P14 are illustrated in Figure 6. During the process of neutron spectrum unfolding, calculated over experimental reaction rate ratios (C/E) of all used reactions have been monitored and they are listed in Table 4. As can be seen from Table 4 all of the C/E ratios are close to

Reaction	R_R [s⁻¹]	Relative uncertainty [%]
$^{nat}Lu(n,x)^{176m}Lu$	4.10×10^{-16}	0.52
$^{nat}Lu(n,x)^{174m}Lu$	8.69×10^{-17}	1.84
$^{93}Nb(n,\alpha)^{90m}Y$	7.13×10^{-19}	1.04
$^{93}Nb(n,2n)^{92m}Nb$	5.46×10^{-17}	0.72
$^{nat}Ni(n,x)^{58}Co$	1.29×10^{-16}	0.33
$^{nat}Ni(n,x)^{57}Ni$	2.41×10^{-18}	0.78
$^{nat}Ni(n,x)^{57}Co$	4.38×10^{-17}	0.97
$^{89}Y(n,\gamma)^{90}Y$	3.34×10^{-19}	2.85
$^{89}Y(n,2n)^{88}Y$	8.09×10^{-17}	0.47
$^{27}Al(n,\alpha)^{24}Na$	1.60×10^{-17}	0.62
$^{197}Au(n,\gamma)^{198}Au$	3.97×10^{-16}	0.11
$^{197}Au(n,2n)^{196}Au$	2.89×10^{-16}	0.19
$^{197}Au(n,2n)^{196m}Au$	1.39×10^{-17}	0.72
$^{59}Co(n,\gamma)^{60}Co$	7.04×10^{-17}	1.23
$^{59}Co(n,\alpha)^{56}Mn$	4.18×10^{-18}	1.45
$^{59}Co(n,p)^{59}Fe$	1.02×10^{-17}	0.83
$^{59}Co(n,2n)^{58}Co$	7.40×10^{-17}	0.24
$^{nat}Fe(n,x)^{56}Mn$	1.51×10^{-17}	1.02
$^{nat}In(n,x)^{115m}In$	1.65×10^{-16}	0.41
$^{nat}In(n,x)^{116m}In$	1.23×10^{-16}	0.62
$^{nat}In(n,x)^{114m}In$	1.54×10^{-16}	0.74
$^{nat}Ti(n,x)^{46}Sc$	6.12×10^{-18}	1.12
$^{nat}Ti(n,x)^{47}Sc$	4.88×10^{-18}	0.33
$^{nat}Ti(n,x)^{48}Sc$	6.42×10^{-18}	0.36

TABLE 3. The set of reaction rates and their uncertainties for observed reactions.

unity which confirm the correctness of the unfolding process. The unfolded neutron energy spectrum has been compared to neutron spectra reported by other authors to check the correctness and to show good agreement in shape. Moreover, the mean energy of the unfolded neutron spectrum is 7.3 MeV which is in agreement with the computed mean energy from the empirical Equation (4). The neutron flux density for a neutron energy higher than 1 MeV reached a value of 5.6×10^9 cm⁻²·s⁻¹ at the position P14.
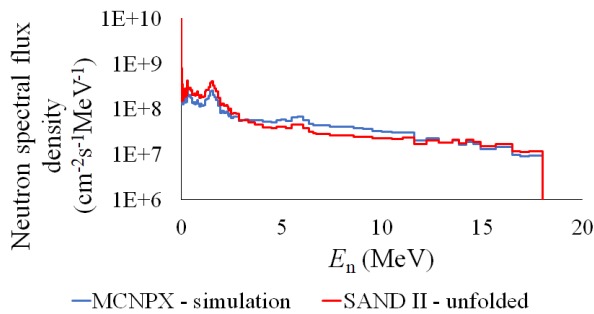

FIGURE 6. The unfolded and determined neutron energy spectra from the source reaction p(20)+Be at the position P14.

Reaction	C/E ratio
$^{197}Au(n,2n)^{196}Au$	0.98
$^{197}Au(n,2n)^{196m}Au$	1.12
$^{197}Au(n,\gamma)^{198}Au$	0.96
$^{27}Al(n,\alpha)^{24}Na$	1.19
$^{115}In(n,n')^{115m}In$	0.96
$^{59}Co(n,p)^{59}Fe$	0.93
$^{59}Co(n,\alpha)^{56}Mn$	1.05
$^{59}Co(n,\gamma)^{60}Co$	1.04
$^{59}Co(n,2n)^{58}Co$	0.90
$^{89}Y(n,2n)^{88}Y$	1.03
$^{89}Y(n,\gamma)^{90m}Y$	0.8
$^{nat}Fe(n,x)^{56}Mn$	1.08
$^{nat}Ti(n,x)^{48}Sc$	0.98
$^{nat}Ti(n,x)^{47}Sc$	1.07
$^{nat}Ti(n,x)^{44}Sc$	0.92
$^{93}Nb(n,\alpha)^{90m}Y$	1.08
$^{93}Nb(n,2n)^{92m}Nb$	1.04
$^{nat}Lu(n,x)^{176m}Lu$	0.99
$^{nat}Lu(n,x)^{174m}Lu$	1.03
$^{nat}Ni(n,x)^{58}Co$	1.01
$^{nat}Ni(n,x)^{57}Ni$	0.91
$^{nat}Ni(n,x)^{57}Co$	0.96

TABLE 4. Calculated over experimental reaction rate ratios.

4. CONCLUSIONS

At the Nuclear Physics Institute of The Czech Academy of Sciences, an energy spectrum of the new neutron field based on the p(20)+Be source reaction at the position P14 has been measured.

The p(20)+Be source reaction produces a neutron field with a broad energy distribution up to 18 MeV and mean energy of 7.3 MeV. The neutron energy spectrum has been determined using the activation foil technique. For proton beam current 12.3 µA the neutron flux density for a neutron energy higher than 1 MeV reached a value of 5.6×10^{9} cm^{-2}·s^{-1} at the position P14. Furthermore, the determined neutron energy spectrum shows good agreement in shape with neutron spectra reported by other authors for similar energies of protons.

The neutron field from the source reaction p(20)+Be has an energy distribution which covers almost the neutron energy spectrum from the d+T reaction and it is suitable for material research for future fusion reactors. It also extends experimental possibilities of beryllium target station NG-2, mostly for measurements, benchmarks of nuclear data, and fast neutron activation analysis.

REFERENCES

[1] International Thermonuclear Experimental Reactor. ITER – The way to new energy. https://www.iter.org/, 2022. [2022-05-25].

[2] The demonstration power plant: DEMO. https://www.euro-fusion.org/programme/demo/, 2021. [2022-05-25].

[3] National Nuclear Data Center Q-value Calculator (Qcalc). https://www.nndc.bnl.gov/qcalc/, 2022. [2022-05-25].

[4] M. Stefanik, P. Bem, M. Majerle, et al. Neutron field study of p(35) + Be source reaction at the NPI Rez. *Radiation Physics and Chemistry* **155**:294–298, 2019. IRRMA-10, https://doi.org/10.1016/j.radphyschem.2018.06.046.

[5] J. Adam, V. Pronskikh, A. Balabekyan, et al. Program Package and Supplements to Activation Analysis for Calculations of Nuclear Reaction Cross Sections. Tech. Rep. JINR-R–10-2000-28, Joint Institute for Nuclear Research (JINR), 2000. https://doi.org/10.1023/a:1010937301028.

[6] M. Winter. WebElements. https://www.webelements.com/, 2022. [2022-05-25].

[7] G. Petzow, F. Aldinger, S. Jönsonn, et al. *Beryllium and Beryllium Compounds.* John Wiley & Sons, Ltd, 2005. https://doi.org/10.1002/14356007.a04_011.pub2.

[8] Y. Uwamino, T. oru Ohkubo, A. Torii, et al. Semi-monoenergetic neutron field for activation experiments up to 40 MeV. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **271**(3):546–552, 1988. https://doi.org/10.1016/0168-9002(88)90318-X.

[9] M. Lone, C. Bigham, J. Fraser, et al. Thick target neutron yields and spectral distributions from the ^{7}Li$(^{d}_{p}$, n) and ^{9}Be$(^{d}_{p}$, n) reactions. *Nuclear Instruments and Methods* **143**(2):331–344, 1977. https://doi.org/10.1016/0029-554X(77)90616-4.

[10] H. Brede, et al. Neutron yields from thick Be targets bombarded with deuterons or protons. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **274**(1):332–344, 1989. https://doi.org/10.1016/0168-9002(89)90399-9.

[11] National Nuclear Data Center. Experimental Nuclear Reaction Data - EXFOR. https://www-nds.iaea.org/exfor/, 2022. [2022-05-25].

[12] Nuclear Physics Institute CAS. http://www.ujf.cas.cz/en/, 2022. [2022-05-25].

[13] D. Pelowitz, J. Durkee, J. Elson, et al. *MCNPX Users Manual Version 2.7.0.* Los Alamos National Laboratory, 2011.

[14] M. Chadwick, M. Herman, P. Obložinský, et al. ENDF/B-VII.1 Nuclear Data for Science and Technology: Cross Sections, Covariances, Fission Product Yields and Decay Data. *Nuclear Data Sheets* **112**(12):2887–2996, 2011. https://doi.org/10.1016/j.nds.2011.11.002.

[15] SAND-II-SNL, PSR-345, UKEA FUS, 1996.

[16] R. Dierckx, M. Nimis, V. Sangiust, M. Terrani. Unfolding methods in neutron spectra measurements by foil activation technique. *Nuclear Instruments and Methods* **105**(1):1–4, 1972. https://doi.org/10.1016/0029-554X(72)90482-X.

[17] L. Packer, J. Sublet, J. Kopecky, et al. Recent Progress in Neutron-, Proton- and Deuteron-induced Reaction Nuclear Data for EAF-2010 and the European Activation System. *Journal of the Korean Physical Society* **59**:1100–1103, 2011. https://doi.org/10.3938/jkps.59.1100.