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MEASUREMENT OF NEUTRON FIELD FUNCTIONALS AROUND A NEUTRON CONVERTER OF 50 GeV PROTONS

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Abstract

The experiment was performed on a pulsed neutron source of the "Neutron" research bench, being created at the U-70 accelerator at National Research Center "Kurchatov Institute" - IHEP, Protvino. Neutrons were generated by the 50 GeV proton beam in the special converter.

As a measurement method, neutron activation analysis was used with a set of threshold activation detectors made of C, Al, Nb, In, Bi materials. The neutron energy thresholds of these detectors are in the range from 1 MeV to 75 MeV. The aluminium activation foils were used to calculate the absolute values of the proton quantities in the exposures.

The results of measurements and calculations are presented in the form of the following functionals: nuclides activity of threshold reactions in detectors at the end of the exposure; reaction rate; neutron fluences with energies greater than the threshold. To estimate these values, the spectra of neutrons, protons and pions were calculated using the particle transport codes MARS and HADRON with the FAN15 as a low-energy block. It was found that neutrons dominate up to 100 MeV, and the charged hadrons contribution to the total reaction rate for a particular nuclide formation can range from 4% to 46%.

INTRODUCTION

Pulsed neutron sources based on high-energy proton beams have a wide range of applications – from transmutation of long-lived radioactive elements to neutron-graphic studies of materials and rapid processes kinetics. Information of the parameters of the neutron field around the proton converter is necessary for these tasks. Similar problems were studied at IHEP (1999 - 2000) with proton beam energy of 1 and 70 GeV [1]. A special research bench "Neutron" was created in 2019 for the extracted 50 GeV proton beam.

The measurements were performed in the field of secondary hadrons, emitted from the side surface of the converter of the bench "Neutron". The converter consists of a lead core 50 × 50 × 300 mm^3 and 40 mm thick polyethylene block surround of the sides. A proton beam with transverse size of 8 mm horizontally and 14 mm vertically dropped on the end face of the lead core along the longitudinal axis. But the beam impact point was shifted horizontally from core center to the right by ~ 8 mm. The intensity of the beam was 1 - 2 bunches per 8.7 s accelerator cycle ($3 \cdot 10^{11}$ protons are in each bunch). As a measurement method, neutron activation analysis was used with a set of threshold activation detectors made of C, Al, Nb, In, Bi materials. The characteristics of the detectors, the threshold reactions, and the identified lines of gamma quanta are fully described in [1].

The aluminium activation foils were used to calculate the number of protons in the exposures. The experiment was performed for three U-70 accelerator runs in the period 2019 - 2021.

RESULTS

The detectors were irradiated in a series of exposures at the points 1, 2, 3 on the thin aluminium substrate placed on the upper converter surface as shown in Fig. 1. The substrate was cut along the beam axis into 12 rectangles (50 × 65 × 0.2 mm^3). The activity A_0 of the ^{22}Na nuclide in these samples at the end of irradiation (a total of $1.3 \cdot 10^{13}$ protons onto converter) is shown in Fig. 2.

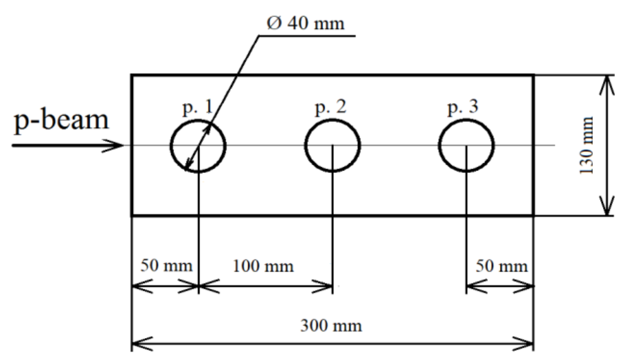

Figure 1: Detectors placement points (p. 1, p. 2, p. 3) on the thin Al substrate.

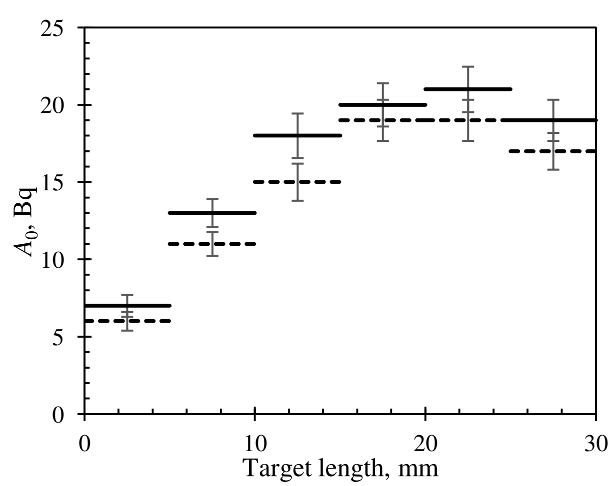

Figure 2: The activities of Na22 in the substrate.

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Table 1: Experimental Reaction Rates and Their Relation to the Calculated Reaction Rates for 50 GeV Protons Energy

Detector → radionuclide	**R_{exp}, 10^{-28} proton^{-1}**			**R_{exp}/R_{cal}**		
	p.1	p.2	p.3	p.1	p.2	p.3
Al →^{24}Na	11.0±6.9%	18.3±6.7%	16.8±6.9%	0.90	0.89	0.93
Al →^{22}Na	2.48±6.5%	5.23±6.5%	5.74±6.5%	2.28	1.93	1.60
Al →^{7}Be	0.125±6.9%	0.454±6.5%	0.709±6.7%	4.11	2.97	2.40
Nb→^{92m}Nb	64±8.2%	111±7.4%	104±7.5%	1.66	1.73	1.73
C →^{11}C	2.68±7.3%	5.82±7.3%	6.43±7.5%	1.30	1.08	0.89
C →^{7}Be	0.884±6.9%	2.02±7.0%	2.43±6.6%	1.21	1.21	1.22
In→^{115m}In	150±6.5%	194±6.5%	171±6.5%	1.02	0.83	0.89
Bi →^{201}Bi	6.47±13.4%	13.9±11.1%	12.3±11%	2.35	1.62	1.02
Bi →^{202}Bi	14.7±8.3%	31.4±8.1%	28.9±8.1%	4.62	3.29	2.18
Bi →^{203}Bi	27.3±15.2%	47.8±12.5%	47.7±12.5%	5.20	3.38	2.58
Bi →^{204}Bi	66.6±8.8%	115±8.8%	96.8±8.8%	8.40	6.03	4.13
Bi →^{206}Bi	69.9±18%	93.5±17.1%	113±15.2%	2.30	1.70	2.01

It should be noted that in this case and for other detectors also, charged hadrons (protons and pions) can make a noticeable contribution to the value of A_0, in addition to neutrons.

The activity A_0 depends on the detector size, the proton beam intensity, the proton energy, the irradiation time, the converter geometry, and the detector position relative to the converter. It is convenient to use the reaction rate R_{exp} to compare the results of repeated or similar experiments. This value is essentially the probability of a particular nuclide formation in the secondary radiation field of one primary proton, normalized to one detector atom. It depends only on the proton energy, the converter geometry, the detection point and experimentally determinates by the formula:

$$R_{exp} = \frac{A_0 \cdot T_0}{N_{at} \cdot N_p (1 - e^{-\lambda T_0})},$$

where T_0 is the irradiation time, N_{at} is the number of atoms in the detector, N_p is the number of protons dropped onto the converter during irradiation, λ is the decay constant.

The reaction rate is also determined by the convolution of the fluences $\Phi(E)$ of neutrons, protons and pions at the detection point with the energy dependences of the cross sections $\sigma(E)$ for the formation of a nuclide in the reactions of these particles with the detector nuclei:

$$R_{cal} = \sum_{i=n,p,\pi} \int \sigma_i(E)\Phi_i(E)\, dE. \quad (1)$$

The experimental reaction rates R_{exp} and the results of calculations by the Eq. (1) in the form of ratios of experimental R_{exp} to the calculated R_{cal} reaction rates are presented in Table 1. The errors of R_{exp} in Table 1 are included measurement errors of A_0 only.

Smooth $\sigma(E)$ dependences were obtained on the basis of experimental cross sections from the EXFOR database [2]. $\Phi(E)$ is the results of calculations using the MARS code [3] provided by I. L. Azhgirei.

From the analysis of Table 1, it follows that acceptable agreement with the calculation is observed for the reactions Al → ^{24}Na, C → ^{11}C, and In → ^{115m}In, but the difference is up to two or more times for remaining nuclides. The accuracy of calculated R_{cal} strongly depends on the availability of correct cross sections for neutrons and charged hadrons, which are clearly insufficient in the literature. A sufficient amount of information is available in EXFOR for the production of ^{22}Na and ^{24}Na nuclides in aluminium and ^{11}C in carbon in the n-, p- and π-reactions, although the data scatter from different authors can reach several tens of percent. There are no data on the cross sections for π-reactions for remaining reactions. To estimate the contributions of pions to the Bi isotopes production, the corresponding cross sections were calculated using the HADRON code [4].

The calculated contributions of hadrons to the experimental reaction rates R_{exp} are shown in Fig. 3.

We made the assumption that, in practice, R_{exp} can be used to estimate the neutron fluence above the thresholds of the corresponding reactions, i.e.

$$\Phi_{exp}(E > E_b) = \int_{E_b}^{E_m} \Phi_{exp}(E) dE \approx \frac{R_{exp}}{\sigma_{av}} \frac{p_n}{100\%},$$

where p_n is the partial contribution of neutrons to the reaction rate R_{exp} in %, E_b and E_m are the threshold and maximum energies. The effective cross sections σ_{av} can be obtained by averaging σ_b over the selected basic set of N neutron fluences spectra $\Phi(E)$, typical for the conditions of the experiment. The value σ_b is determinate as:

$$\sigma_b = \int_{E_b}^{E_m} \sigma(E)\Phi(E) dE \Big/ \int_{E_b}^{E_m} \Phi(E) dE. \quad (2)$$

The fluence spectra for proton energy of 50 and 10 GeV were used to calculate σ_b according to Eq. (2). Neu-

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tron spectra for proton energy of 10 GeV were calculated for the same geometry as for 50 GeV protons by HADRON code with a low-energy cluster FAN15 [5]. The threshold energies E_b in Eq. (2) were determined from the point of increasing $\sigma(E)$ from 0 to 0.1 of their maximum values. The results of calculating the cross sections σ_b by Eq. (2) are shown in Fig. 4 and σ_{av} – in Table 2.

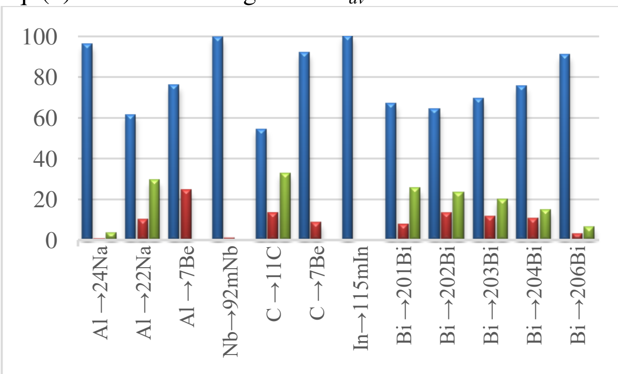

Figure 3: Calculated contributions of hadrons to the reaction rates in %. Neutrons contribution shows by blue colours, protons – red, pions – green.

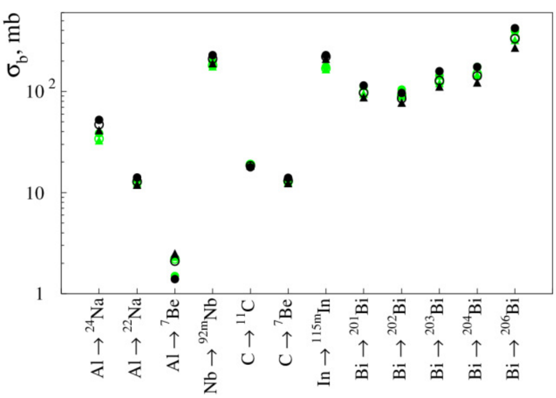

Figure 4: The neutron reactions cross sections weighted by the calculated fluence spectra at three points. Green points correspond to 10 GeV proton beam, black – 50 GeV. (●, ● – p. 1; ○, ○ – p. 2; ▲, ▲ – p. 3).

The average cross sections for three points on the converter surface are close despite the fact that the energy distributions of neutron fluences at these points differ from each other. Averaging over the neutron fluences for 10 GeV proton beam gives to us very close results. The obtained average cross sections can be used to estimate the above-threshold neutron fluences also for other targets with different proton beam energies. The results are shown in Table 2.

As it can be seen from the data in Table 2, the experimental fluences agree with the calculation for the reactions In → ^{115m}In (12%), Al → ^{24}Na (9%), C → ^{11}C (4%), C → ^{7}Be (11%), Bi → ^{201}Bi (29%). The difference reaches factor two and higher for remaining reactions. Under the assumption that the neutron fluences emitted from other side surfaces of the converter are close to the data in Table. 2, it is possible to estimate the total lateral neutron yield also.

Table 2: Neutron Fluences Above the Threshold Energies, Averaged Over Three Points

Reaction	E_b, **MeV**	σ_{av}, **mb**	$\Phi(E>E_b)$, **n/cm²/p**	
			Calculated	Experiment
In→^{115m}In	0.8	220	8.78E-02	7.82E-02
Al→^{24}Na	6.8	47	3.46E-02	3.18E-02
Nb→^{92m}Nb	9.6	210	2.61E-02	4.47E-02
C →^{11}C	22	18	1.39E-02	1.45E-02
Bi →^{206}Bi	26	341	1.22E-02	2.59E-02
Al →^{22}Na	30	13	1.11E-02	2.12E-02
C →^{7}Be	31	4	1.10E-02	1.24E-02
Bi →^{204}Bi	45	146	8.29E-03	4.93E-02
Bi →^{203}Bi	55	133	7.04E-03	2.23E-02
Bi →^{202}Bi	64	86	6.25E-03	1.90E-02
Bi →^{201}Bi	75	99	5.42E-03	7.59E-03
Al →^{7}Be	114	2	3.62E-03	1.48E-02

CONCLUSION

Experimental data for the hadrons yields from the neutron converter lateral surface of known geometry have been obtained with acceptable accuracy for 50 GeV proton beam energy. Reaction rates R_{exp} can use to check of the adequacy of calculated cross sections threshold. An application of methods of effective cross sections and threshold reactions has been attempted to estimate the above-threshold neutron fluences. The hadrons component compositions at the measurement points and their contributions to R_{exp} have been calculated.

An application of methods of effective cross sections and threshold reactions has been attempted to estimate the above-threshold neutron fluences. Acceptable agreement between the experimental and calculated fluences of above-threshold neutrons has been obtained for the reactions In → ^{115m}In, Al → ^{24}Na, C → ^{11}C, C → ^{7}Be, Bi → ^{201}Bi. The discrepancies for remaining reactions are mainly explained by the lack of reliable data on the cross sections. Experimental fluences have been used to estimate the total lateral neutron yields. The values of 122, 50, 23, 19 and 12 neutrons per proton have been received for the neutron yields above the threshold of 0.8, 6.8, 22, 31 and 75 MeV, respectively.

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