Measurement of neutron field functionals around a neutron converter of 50 GeV protons

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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 the kinetics of fast processes. Information on the parameters of the neutron field around the proton converter is necessary for these tasks.

The experiment was done on a pulsed neutron source of the "Neutron" research stand, being created at the U-70 accelerator at National Research Center “Kurchatov Institute” – IHEP, Protvino. Neutrons were generated by the fast extracted 50 GeV proton beam in the special converter (50×50×300 mm^3 lead core with 40 mm side plates made of polyethylene sheet). The dimensions of the proton beam at the point of impact were 8 mm horizontally and 14 mm vertically. A neutron activation analysis was used with a set of threshold activation detectors made of C, Al, Nb, In, Bi materials. The neutron thresholds of these detectors were in the range from 1 MeV for indium to 75 MeV for bismuth. The aluminum activation foils were used to calculate the absolute values of the protons quantities in the exposures.

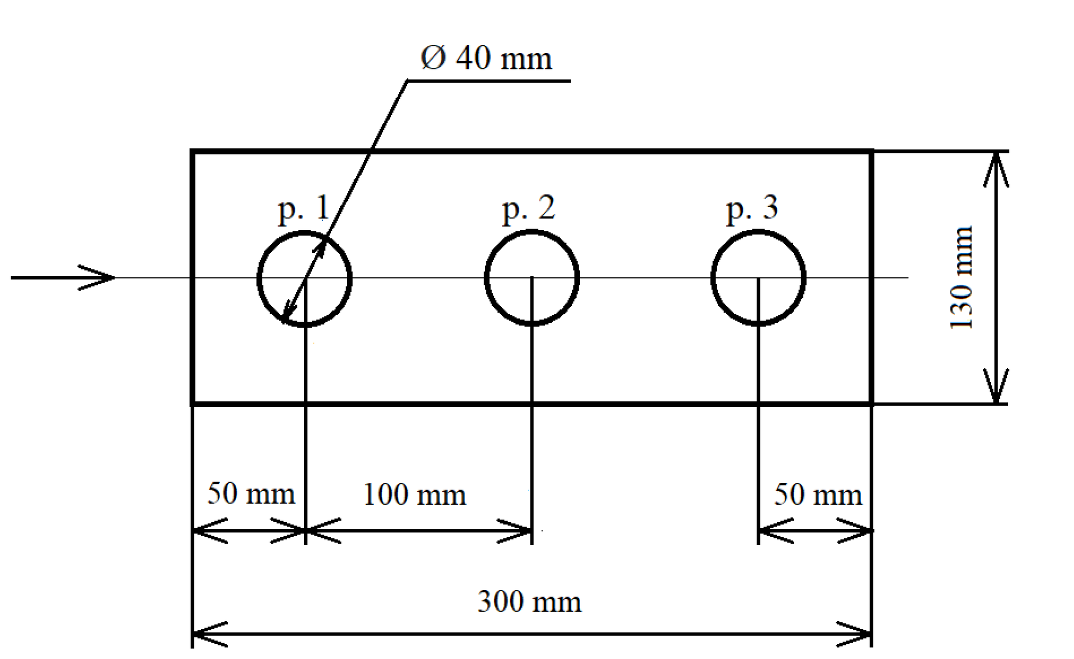


Fig. 1. Placement points (p.1 – p.3) of detectors on the thin Al substrate. The arrow indicate the direction of the incident proton beam.

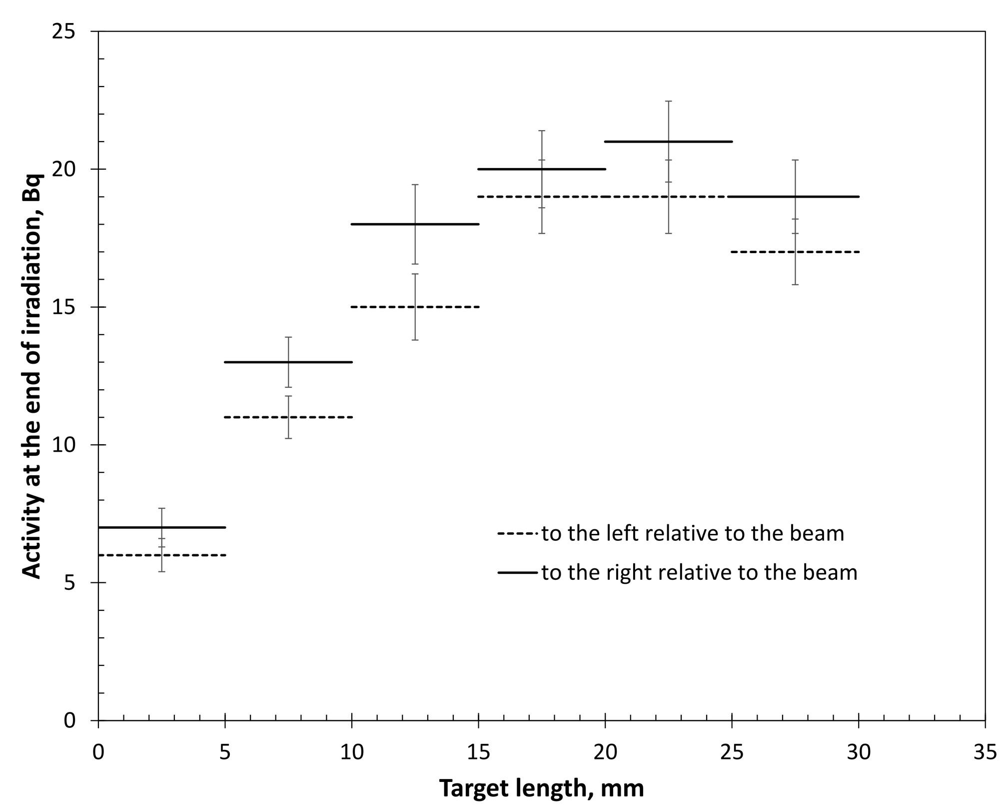


Fig. 2.Activities A_0 (^{22}Na) induced in the substrate by hadrons emerging from the upper surface of the converter. $1.3\cdot10^{13}$ protons were droped onto the converter.

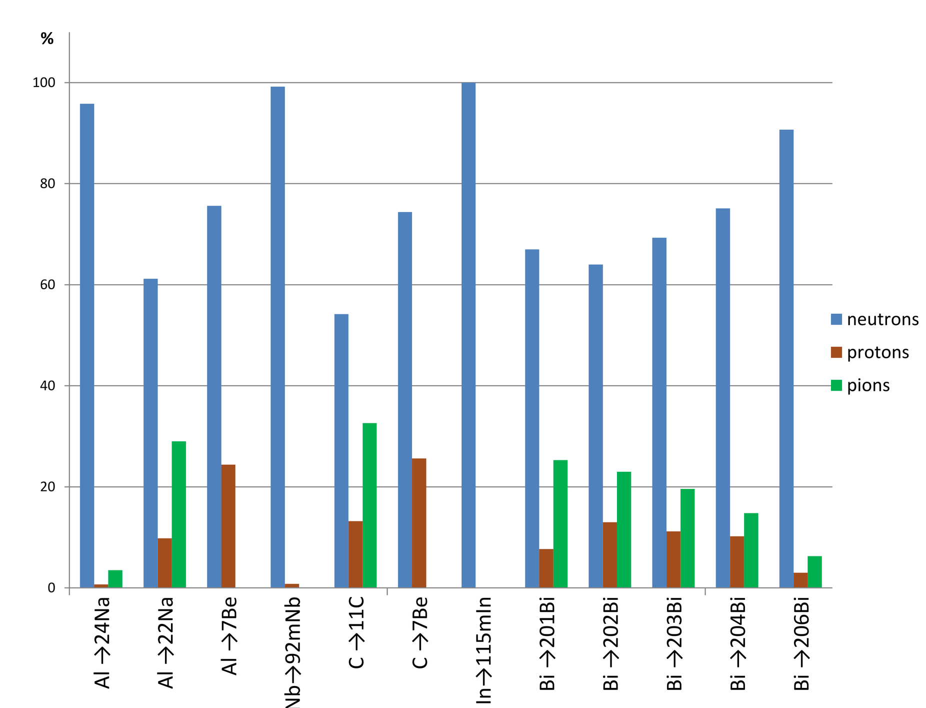
The detectors were irradiated in a series of exposures on the upper converter surface at the points 1–3 of the thin aluminum substrate (Fig. 1). After the first exposures, the substrate was cut along the beam axis into 12 rectangles (50 × 65 × 0.2 mm^3), the activity of which at the end of irradiation (A_0) with respect to the ^{22}Na nuclide is shown in Fig. 2. It should be noted that here and for other detectors, charged hadrons (protons and pions) can make a noticeable contribution to the value of A_0, in addition to neutrons.

The measurement results are the values of the activity A_0 of nuclides in the detector at the end of the irradiation. The activity depends on:

- the size of the detector,
- the intensity of the proton beam,
- the energy of the protons,
- the irradiation time,
- the geometry of the target,
- the position of the detector relative to the target.

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

*) - the errors of R_{exp} include only measurement errors of A_0.



Calculated contributions of hadrons to the R_{cal} in %.

Reaction rate R_{exp}, in the meaning is the probability of a particular nuclide formation in the reactions of secondary radiation from one primary proton with one detector atom. This value depends only on the energy of protons, the geometry of the target and the point of detection.

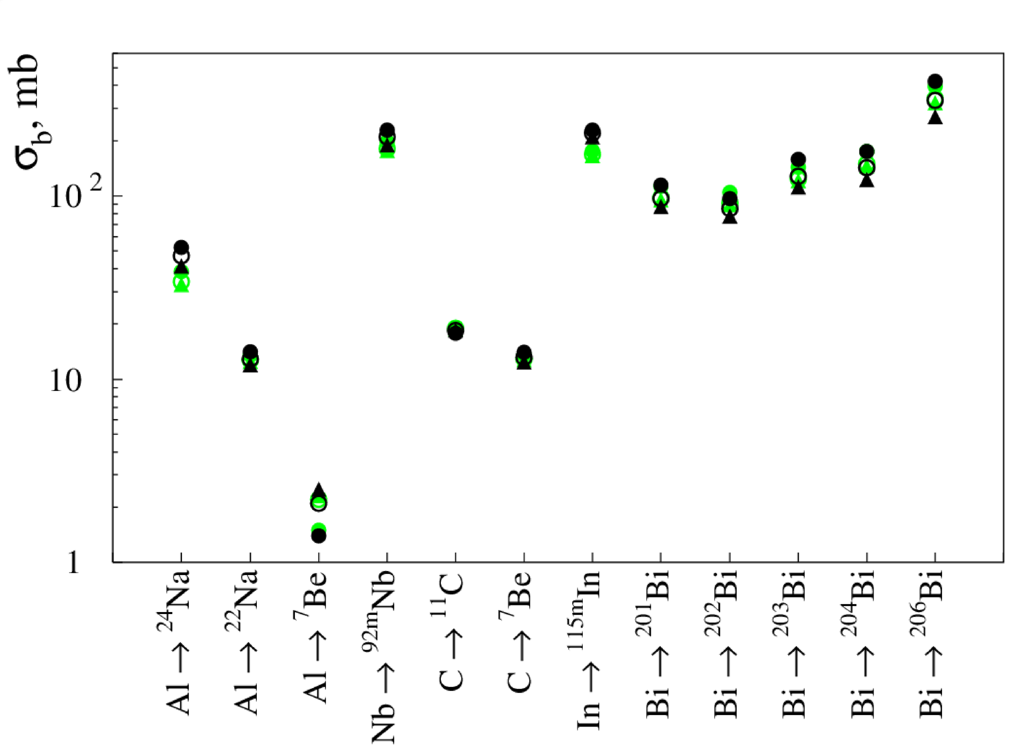
It experimentally determinates by the formula:

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

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

The reaction probability is also determined by the convolution of the distributions of fluencies Φ(E) of neutrons, protons and pions at the detection point with the energy dependences of the cross sections for the formation of a nuclide σ(E) in the reactions of these particles with the detector nuclei:

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



Average neutron cross sections of reactions, weighted by the calculated fluence spectra at three points on the target: green points - for a beam proton energy of 10 GeV, black - 50 GeV. (●, ● – p.1; ○, ○ – p.2; ▲, ▲ – p.3).

Neutron fluencies averaged over three points

Reaction	E_b, MeV	<σ>, mb	Φ(E>E_b), n/cm^2/p	
			Calculated	Experiment
In→^{115m}In	0.8	220	8.78E-02	7.82E-02
Al→^{24}Na	6.8	47.0	3.46E-02	3.18E-02
Nb→^{92m}Nb	9.6	210	2.61E-02	4.47E-02
C →^{11}C	21.5	18.3	1.39E-02	1.45E-02
Bi →^{206}Bi	26.2	341	1.22E-02	2.59E-02
Al →^{22}Na	30.2	13.0	1.11E-02	2.12E-02
C →^{7}Be	30.5	4.27	1.10E-02	1.24E-02
Bi →^{204}Bi	45.2	146	8.29E-03	4.93E-02
Bi →^{203}Bi	54.9	133	7.04E-03	2.23E-02
Bi →^{202}Bi	64.2	86.4	6.25E-03	1.90E-02
Bi →^{201}Bi	74.7	99.5	5.42E-03	7.59E-03
Al →^{7}Be	114	2.0	3.62E-03	1.48E-02

In practice, R_{exp} can be used to estimate the neutron fluence above the thresholds of the corresponding reactions, i.e.

$$\Phi_{exp}(E > E_b) = \int_{E_b}^{E_{max}} \Phi_{exp}(E) dE \approx \frac{R_{exp}}{\bar{\sigma}} \frac{p_n}{100\%},$$

where p_n is the partial contribution of neutrons to the reaction rate R_{exp} in %, E_b and E_{max} are threshold and the maximum energies.

The effective cross sections $\bar{\sigma}$ were obtained by averaging σ(E) over the selected basic set of N neutron fluences spectra Φ (E), typical for the conditions of the experiment.

$$\bar{\sigma} = \frac{1}{N}\sum \sigma_b, \quad \sigma_b = \int_{E_b}^{E_{max}} \sigma(E)\Phi(E)dE \Big/ \int_{E_b}^{E_{max}} \Phi(E)dE.$$

Smooth σ(E) dependences are fitting of experimental cross sections from the EXFOR database

Conclusion

The results of measurements and calculations are presented in the form of the following functionals: the activity of nuclides of threshold reactions in detectors at the end of the exposure; the reaction rates; the fluenicies of neutrons 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 low-energy block. It was found that neutrons predominate up to 100 MeV, and the contribution of charged hadrons to the total reaction rate for the formation of a particular nuclide can range from 4% to 46%.

Satisfactory results have been obtained for comparing the experimental fluences of above-threshold neutrons for the reactions In → ^{115m}In, Al → ^{24}Na, C → ^{11}C, C → ^{7}Be, Bi → ^{201}Bi with the calculated data. The discrepancies in the remaining reactions are mainly due to the lack of reliable data on the cross sections. Experimental fluences were used to estimate the total lateral neutron yields. The yields for neutrons above the threshold of 0.8, 6.8, 22, 31 and 75 MeV were 122, 50, 23, 19 and 12 neutrons per proton, respectively.