BORON NITRIDE AS A TARGET FOR PROTON-INDUCED REACTIONS ON NITROGEN*

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Nitrogen is one of the most common elements in the human body, beyond hydrogen, oxygen, and carbon. Proton beams used in therapy induce nuclear reactions on these elements that cause a loss of fluence along the beam path. These reactions often lead to production of β^+ emitters with relatively short half-lives (less than 20 minutes). While the reaction on carbon leading to production of ^{11}C has been extensively studied, the cross section for reactions on nitrogen and oxygen are not sufficiently known, particularly at proton energies above a few tens of MeV. This contribution presents the results of an experiment, where solid boron nitride targets were used to study nuclear reactions induced by protons with energy below 60 MeV on nitrogen. The proton beam was delivered by the AIC-144 cyclotron of the Institute of Nuclear Physics in Kraków. As a result, the cross section of $^{14}\mathrm{N}(p,x)^{13}\mathrm{N}$ reaction was obtained.

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1. Introduction

Proton therapy is a method of cancer treatment that uses a proton beam to irradiate the diseased tissue. The biggest advantage of this form of therapy is the fact that the maximum of the energy loss of protons is close to the

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end of their range. When protons pass through the matter, they can induce nuclear reactions that cause a reduction of the beam flux and affect the dose distribution [1].

The increasing number of radioactive nuclei produced in the target depends on the cross sections of the involved reaction channels. After the irradiation, the activity of the target decreases exponentially. In the case of BN, two β^+ emitters are produced: ^{13}N and ^{11}C. The reactions with the lowest Q value are listed in Table 1. In this experiment, it was not possible to distinguish between reactions with different products, such as deuterium and a proton–neutron pair, so a letter x is used in the notation. Since ^{11}C is produced in reactions induced on both nitrogen and boron, it was not possible to obtain the cross section of $^{14}\mathrm{N}(p,x)^{11}\mathrm{C}$ reaction.

Table 1. Reactions induced by protons on boron and nitrogen, their Q values [2], and half-lives of produced β^+ emitters [3].

Target element	Reaction	Q value [MeV]	Residue	$T_{1/2}$ [min]
B	$^{11}\mathrm{B}(p,n)$	-2.76	^{11}C	20.364(14)
N	$^{14}\mathrm{N}(p,\alpha)$	-2.92		
	$^{14}\mathrm{N}(p,d)$	-8.33	^{13}N	9.965(4)

2. Experiment

The BN samples were prepared in the form of pastilles with a radius of 5 mm. They were sintered from BN powder of 99% purity at the UNIPRESS Institute of High Pressure Physics. This process was carried out at a temperature of 1000°C and a pressure of less than 7.7 GPa. The thickness of the targets was between 1.4 and 2.3 mm.

The experiment was done at the Institute of Nuclear Physics PAS in Kraków in March 2023. Three chosen targets were stacked next to each other and irradiated simultaneously by a proton beam delivered by the AIC-144 cyclotron. Two irradiations were carried out using the same set of targets (see Table 2 for details).

Table 2. Details of irradiations and measurements.

Energy [MeV]	Flux [cm^{-2}s^{-1}]	Irradiation time [s]	Measurement time [min]
58	1.64×10^8	354.8	100
40	5.69×10^7	751.8	80

After the irradiation, the activity of the targets was measured. The detection setup, shown in Fig. 1, was constructed at the Faculty of Physics of the University of Warsaw. It consists of three pairs of $LaBr_3$ detectors (1 inch on top and 1.5 inch on bottom). The rotating disk between them made it possible to measure the activity of up to 16 samples, but in this particular experiment, only three targets were irradiated. Each target was placed between two detectors and the activity was measured continuously. Measurements of single spectra suffer from the influence of radioactivity of neighbouring samples [4] and require correction procedure [5]. Therefore, the experimental results, presented in this paper, are based on coincidence detection of two 511 keV photons following e^+e^- annihilation after β^+ decay.

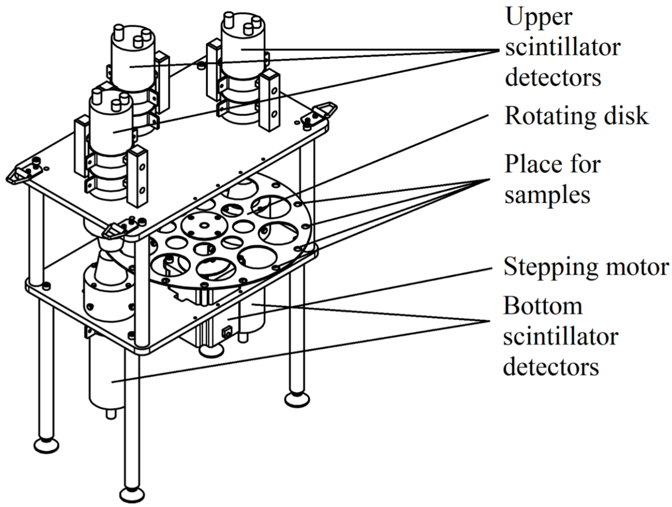

Fig. 1. Detection setup.

3. Results

After the irradiation, the activity A of the target decreases with time according to a formula that is the sum of the exponential functions corresponding to the produced isotopes:

$$A(t) = A_{\mathrm{N}}\, \mathrm{e}^{-t/t_{\mathrm{N}}} + A_{\mathrm{C}}\, \mathrm{e}^{-t/t_{\mathrm{C}}} \,, \tag{1}$$

where A_{N} and A_{C} are activities of, respectively, ^{13}N and ^{11}C at the end of the irradiation and t_{N}, t_{C} are the lifetimes of these isotopes. This function was fitted to the experimental results (see Fig. 2) in order to obtain the value of A_{N}, and on this basis, the cross section of $^{14}\mathrm{N}(p,x)^{13}\mathrm{N}$ reaction.

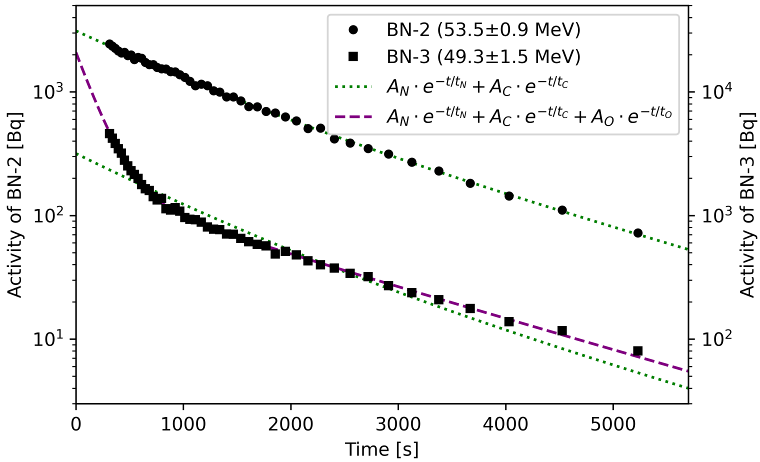

Fig. 2. The decay curve of two of the BN targets. The lower one (sample BN-3) shows unexpected activity from ^{15}O decay.

In the case of one of the targets, the measured decrease of activity is much better described by a function that takes into account also the activity of ^{15}O (see Fig. 2). This was observed in both of the measurements in which the same sample was used. As this isotope cannot be produced in any of the proton-induced reactions on nitrogen, this leads to a conclusion that the BN sample was contaminated with another element — oxygen. Consequently, the results from this target were not used for the determination of cross section.

For the remaining two targets, the activity at the end of the irradiation $A_{\rm N}$ was obtained from the fit of function (1). This made it possible to determine the cross section according to the formula

$$\sigma = \frac{A_{\rm N}}{N_{\rm T}\, I\, (1 - {\rm e}^{-\lambda t_{\rm EOB}})}\,, \tag{2}$$

where $N_{\rm T}$ — number of target nuclei, I — beam flux, λ — decay constant of ^{13}N, and $t_{\rm EOB}$ — irradiation time ("end of beam" time). The obtained cross sections for four proton energies are shown in Fig. 3 and listed in Table 3. Beam energy loss in the targets was calculated using the Bethe–Bloch formula. The experimental data from works of Kovacs *et al.* [6], Valentin [7], and Sajjad *et al.* [8] are shown for comparison. Our results are in good agreement with the measurements of Valentin performed half a century ago. The precision of our measurements is better compared to previous ones.

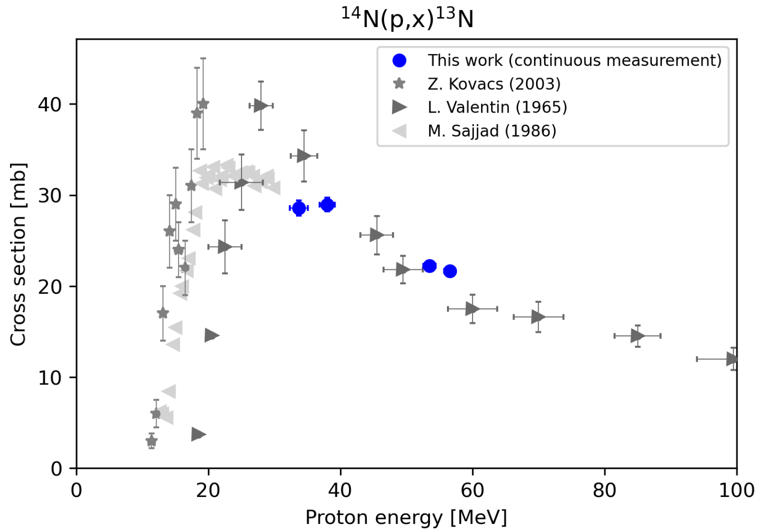

Fig. 3. (Colour on-line) Cross section of the $^{14}\mathrm{N}(p,x)^{13}\mathrm{N}$ reaction as a function of proton energy. Blue/black marks correspond to the results of this work and grey points correspond to experimental data from the literature.

Table 3. Cross section of the $^{14}\mathrm{N}(p,x)^{13}\mathrm{N}$ reaction.

Energy [MeV]	Cross section [mb]
56.5 ± 0.9	21.7 ± 0.5
53.5 ± 0.9	22.2 ± 0.4
38.0 ± 1.2	29.0 ± 0.8
33.7 ± 1.3	28.6 ± 0.8

4. Conclusions

Cross sections for the $^{14}\mathrm{N}(p,x)^{13}\mathrm{N}$ reaction for four proton energies were obtained using solid BN targets. The results were compared to existing experimental data. The available cross-section data for this reaction includes mostly results for energies under 40 MeV. In the studied energy range, the only available data come from the work of Valentin published in 1965 [7]. Our results are in good agreement with this data. Solid BN targets turned out to be useful for this type of measurement. The experiment allowed also to detect unexpected oxygen contamination in one of the BN targets.

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