MEASUREMENT OF PARAMETERS OF NEUTRON RADIATION ON THE ACCELERATOR-BASED EPITHERMAL NEUTRON SOURCE*

M. I. Bikchurina, T. A. Bykov, D. A. Kasatov, Ia. A. Kolesnikov, I. M. Shchudlo, S. Yu. Taskaev,
BINP and Novosibirsk State University, Novosibirsk, Russia
K. A. Martianov, LLC "BINP-Plasma", Novosibirsk, Russia

Abstract

Treatment of oncological diseases using Boron Neutron Capture Therapy (BNCT) is an important issue of our time. Cancer cells accumulate a boron-containing drug, after which they are irradiated with a beam of epithermal neutrons, a nuclear reaction $^{10}B(n,\alpha)^7Li$ occurs, and the products of a nuclear reaction destroy these cells. In BNCT, it is generally accepted that the total dose of ionizing radiation consists of four components: boron dose, dose from fast neutrons, dose from thermal neutrons, and dose of gamma radiation. Dose values and their ratio strongly depend on the neutron flux; therefore, the measurement of the neutron flux (yield) is an urgent task. In this work, the neutron yield was measured by the activation of the target with the radioactive isotope beryllium-7, which is formed in the reaction of neutron generation $^7Li(p,n)^7Be$. It was found that the neutron yield from a specifically manufactured lithium target is in good agreement with the calculated one, which is important for planning therapy.

INTRODUCTION

An accelerator based epithermal neutron source for the development of boron neutron capture therapy (BNCT), a promising method for the treatment of malignant tumors, is proposed, created and is functioning at the Budker Institute of Nuclear Physics [1,2]. The neutron source consists of a tandem accelerator of charged particles of an original design, a lithium neutron-generating target, for generating neutrons as a result of the $^7Li(p,n)^7Be$ reaction, and a system for forming a therapeutic beam of epithermal neutrons. The total dose of ionizing radiation consists of four components: boron dose, dose from fast neutrons, dose from thermal neutrons, and dose of gamma radiation. Dose values and their ratio strongly depend on the spectrum and neutron flux.

DESIGN OF THE ACCELERATOR

The neutron source consists of a tandem accelerator of charged particles of an original design, a lithium neutron-generating target and a system for forming a therapeutic beam of epithermal neutrons, Fig. 1.

In a tandem accelerator, a surface plasma source using a Penning discharge with hollow cathodes is used to generate negative hydrogen ions. A beam of negative hydrogen ions with an energy of 20-23 keV and a current of up to 10 mA is focused with magnetic lenses and injected into a tandem

electrostatic accelerator. In an accelerator, negative hydrogen ions are accelerated by a voltage applied across six high-voltage electrodes. In a gas stripping target made in the form of a cooled tube with argon inlet in the middle and installed inside a high-voltage electrode, negative ions lose electrons and turn into protons, which are accelerated to an energy equal to twice the potential. Then the proton beam is delivered to the lithium target for neutron generation as a result of the threshold nuclear reaction $^7Li(p,n)^7Be$.
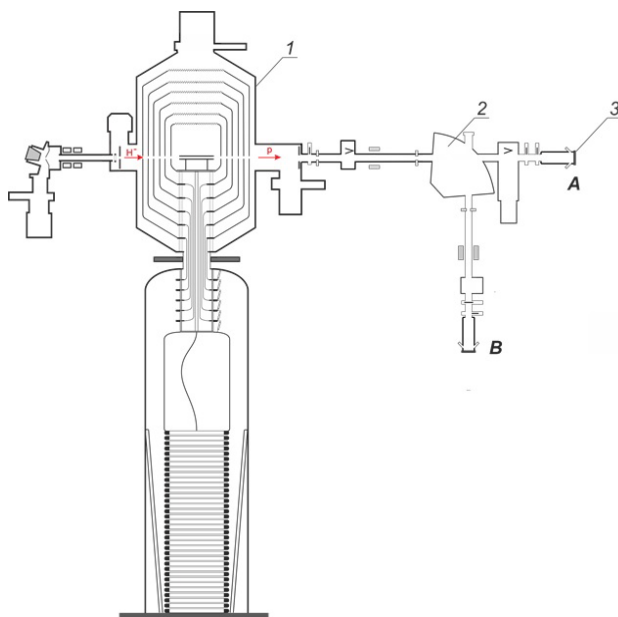

Figure 1: Tandem accelerator with vacuum insulation: 1 – accelerator, 2 – bending magnet, 3 – lithium neutron generating target. The lithium target is placed in the horizontal proton beam transport path (position A) or in the vertical (position B).

EXPERIMENTAL RESULTS

A total of 15 sessions of neutron generation were carried out; used 13 lithium targets. In the manufacture of all 13 targets, only a new copper substrate was used and a new lithium layer was always deposited.

Since the products of the $^7Li(p,n)^7Be$ reaction are not only a neutron, but also a radioactive atomic nucleus beryllium-7, measuring the number of ^7Be nuclei makes it possible to unambiguously determine the number of generated neutrons.

The radioactive atomic nucleus ^7Be, as a result of electron capture, is converted back to lithium-7 with a half-life of 53.22 days. In 10.3% of cases, decay is accompanied

by the emission of a 478 keV photon. If we do not allow the propagation of beryllium from a lithium target, then measuring the activation of the target makes it possible to determine the number of produced ^{7}Be nuclei, which is equal to the number of generated neutrons, which was done. Before the measurement, the target assembly is removed from the setup, disassembled, the actual lithium target is taken out of it, which is placed in a transparent plastic bag and placed along the spectrometer axis so that the surface of the lithium layer is directed towards the spectrometer and the distance between the surface of the lithium layer and the entrance window of the detector was equal to 1854 mm. According to the law of radioactive decay, the number of non-decayed atoms at time t is related to the initial (at time t = 0) number of atoms by the ratio

$$\frac{N(t)}{N_0} = e^{-\frac{0,693\,t}{t_{1/2}}}.$$

The dependence of the neutron yield in the ^{7}Li(p,n)^{7}Be reaction on the proton energy is given in [3] and can be calculated using the PINO program using reference [4] given in [5]; they are shown in Fig. 2.
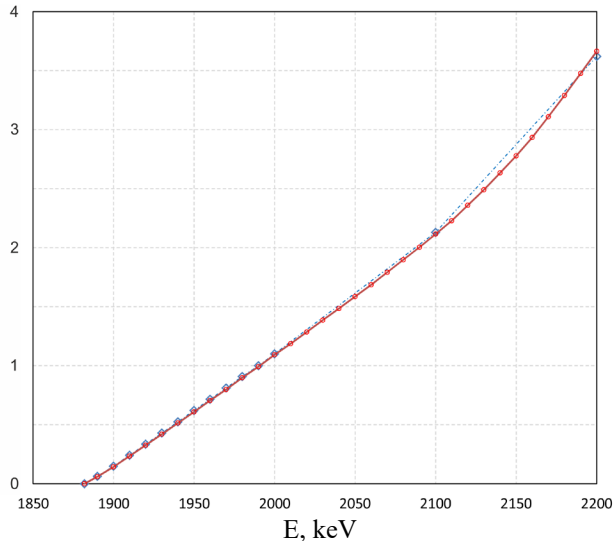
Y, relative units

Figure 2: Dependence of the neutron yield Y on the proton energy E in the ^{7}Li(p,n)^{7}Be reaction: ◊ – from [3], ○ – calculated by the PINO program [4].

Since the ^{7}Li(p,n)^{7}Be reaction is threshold (the reaction threshold is 1882 keV), the neutron yield strongly depends on the proton energy. So, with a decrease in the energy of protons from 2 MeV by 1%, the neutron yield decreases by 18%, and from 2.2 MeV – by 11%.

The energy calibration of the accelerator neutron source was carried out using two threshold reactions: ^{7}Li(p,n)^{7}Be – 1.882 MeV, ^{9}Be(p,n)^{9}B – 2.057 MeV. For the second reaction, a beryllium disk 32 mm in diameter and 9.7 mm thick was tightly attracted to the copper substrate of the target through an indium-gallium alloy and irradiated with a proton beam in position A. A neutron detector with a GS20 lithium-containing scintillator (The Saint-Gobain Crystals, USA) installed in front of the target was used to measure the dependence of the recorded signal on the proton energy. The measurement results and the dependence of the neutron yield on energy calculated by the PINO program are shown in Fig. 3.
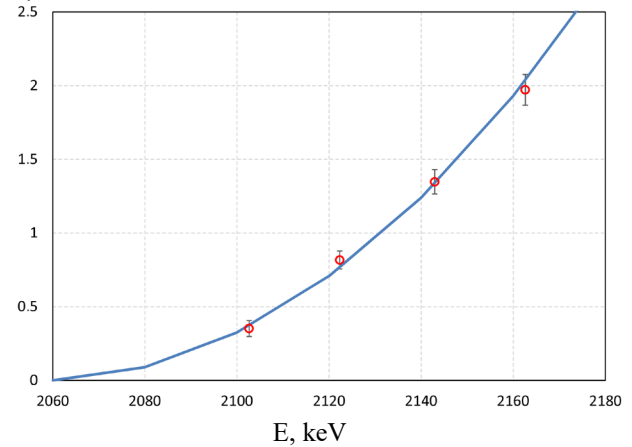
Y, relative units

Figure 3: Dependence of the neutron yield Y on the proton energy E in the ^{9}Be(p,n)^{9}B reaction: ○ – measured, solid line – calculated by the PINO program [4].

Subsequently, a bending magnet was used as an energy analyzer. The position of the proton beam in the center of the target was controlled by the following diagnostic tools: i) a video camera recording luminescence of lithium under the bombardment of protons [6], ii) five thermocouples placed inside the copper disk of a lithium target, one in the center, the other four at a distance of 18 mm from the center, uniformly spaced in azimuth, and iii) as indicated by two small-sized neutron detectors with a boron-enriched polystyrene cast scintillator glued to the vacuum chamber of the target assembly near the lithium target. The proton beam on the target surface had a characteristic size of 3 cm.

When calculating the neutron yield, three corrections were taken into account. First, the percentage of lithium-7 was taken into account. For deposition, we used natural or lithium enriched with the isotope lithium-7, produced by the Novosibirsk plant of chemical concentrates. In the batch of natural lithium, the lithium content was 99.95%; in enriched lithium, the atomic fraction of lithium-7 was 99.988%. Secondly, the used natural lithium contains impurities at a concentration of 0.044%. The weighted average value of the atomic number of impurities, in accordance with the product passport, is 15. This value is 5 times higher than the atomic number of lithium, therefore, the deceleration of a proton, determined by interaction with electrons, is 5 times more effective on impurities than on lithium. This means that impurities in a concentration of 0.044% reduce the neutron yield by 0.22%. In lithium enriched with the isotope lithium-7, the concentration of impurities is 0.012%, which means that their presence reduces the neutron yield by 0.06%. Third, let us take into account the secondary emission of electrons when measuring the proton current; the measured proton fluence is overestimated by 1%. The result is graphically shown in Fig. 4 [7].
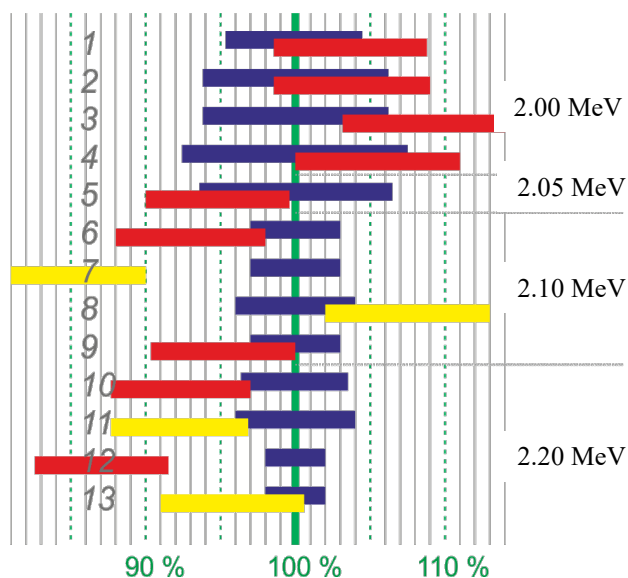
Figure 4: The result of the study comparing the measured neutron yield with the calculated one: from top to bottom - targets in order, blue rectangles - intervals of the calculated number of neutrons, red and yellow – intervals of the measured number of neutrons (red – natural lithium, yellow – enriched with lithium-7 isotope). On the right are the characteristic values of the proton energy.

It can be seen that the measured amount of beryllium-7 is always slightly higher than the calculated one if the target is placed in the horizontal channel (sessions 1-3 and 8) and almost always less if the target is placed in the vertical channel (sessions 4 – 7 and 9 – 13). Perhaps this is due to the large size of the proton beam and its displacement over the target surface, due to which part of the proton beam could fall into the region outside the region of lithium deposition.

PROSPECTS

The obtained result is planned to be used in determining the dose received by patients during therapy at the BNCT clinic in Xiamen (China), equipped with an accelerating neutron source manufactured by TAE Life Sciences (USA).

CONCLUSION

For the first time, the neutron yield from a lithium target was measured by its activation with the radioactive isotope beryllium-7 using a γ-radiation spectrometer based on a semiconductor detector made of highly pure germanium The agreement of the measured yield to the calculated one is shown, which is important when planning boron neutron capture therapy.

REFERENCES

[1] W. Sauerwein, A. Wittig, R. Moss and Y. Nakagawa (Eds.), *Neutron Capture Therapy: Principles and Applications*. Springer, 2012. `doi:10.1007/978-3-642-31334-9`

[2] S. Taskaev *et al.*, "Neutron Source Based on Vacuum Insulated Tandem Accelerator and Lithium Target", *Biology*, vol. 10, 350, Apr. 2021. `doi:10.3390/biology10050350`

[3] C. Lee and X. Zhou, "Thick Target Neutron Yields for the ^{7}Li(p,n)^{7}Be Reaction near Threshold", *Nucl. Instrum. Methods Phys. Res., Sect. B*, vol. 152, pp. 1-11, 1999. `doi:10.1016/S0168-583X(99)00026-9`

[4] `https://exp-astro.de/pino/`

[5] R. Reifarth, M. Heil, F. Käppeler and R. Plag, "PINO – a tool for simulating neutron spectra resulting from the ^{7}Li(p,n) reaction", *Nucl. Instrum. Methods Phys. Res., Sect. A,* vol. 608, pp. 139-143, 2009. `doi:10.1016/j.nima.2009.06.046`

[6] A. Makarov, E. Sokolova, S. Taskaev, "Luminescence of a lithium target irradiated with a proton beam", *Instrum. Exp. Tech.*, vol. 64, pp. 30-33, Jan. 2021. `doi:10.1134/S0020441220060184`

[7] M. Bikchurina *et al*., "The measurement of the neutron yield of the ^{7}Li(p,n)^{7}Be reaction in lithium targets", *Biology*, vol. 10, 824, Aug. 2021. `doi:10.3390/biology10090824`