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THE COMPUTER MODEL OF A THERMAL DELAYED NEUTRON FLUXES FORMING SYSTEM FOR NUCLEAR MEDICINE

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In the work the computer model of a cell of a system for generating fluxes of therapeutic beams of delayed neutrons, based on the use of delayed fission neutrons, was developed in the Geant 4 environment. The principle of such a neutron source is that when a powerful electron beam interacts with a combined tungsten target and a target containing fissile material, a fission reaction occurs; as a result of which neutrons are emitted. If we move a target activated in this way several tens of meters into a neutron flux generation system consisting of a heater, protection, collimator and reflector, we will obtain a compact neutron source for nuclear medicine. A significant advantage of such a neutron source is the absence of gamma background from the electron accelerator and the combined target, and a bulky protection system is not required. In the Geant 4 environment, the geometry of this cell was developed and a series of experiments were carried out with 10^7 neutrons. The QGSP BIC HP physical sheet was used. A study of neutron energy spectra showed that more than half of the neutrons whose fluxes are formed using such a cell of the formation system have an energy <100 keV, which is suitable for use for therapeutic purposes. Analysis of the data obtained in a computer experiment made it possible to develop a modified cell of the system for generating streams of therapeutic beams of delayed neutrons, which differs from the basic one by the presence of a solid polyethylene moderator with holes for activated targets and a graphite reflector. Analysis of the data obtained showed that in this case the number of thermal neutrons hitting the detector increases 10 times compared to the base cell, and the energy of 80% of the particles does not exceed 5 keV, which is much better suited for therapeutic purposes.
Keywords: *Therapeutic beams; Delayed neutrons; Electron accelerator; Computer model; Neutron capture therapy*
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INTRODUCTION

As you know, cancer is one of the most common diseases in the world. According to the American Cancer Society, more than 10,000000 people have been diagnosed with cancer worldwide in 2022, only there were approximately 1.9 million new cancer cases in the United States, including 609,360 deaths. Despite the fact that great progress has been made in medicine, humanity still needs to invent improved cancer therapy. One of the key challenges is the use of nuclear medicine.

In nuclear medicine, high-energy electrons from electron accelerators are traditionally used to treat superficial tumors. X-ray radiation and gamma therapy are used for deep-lying affected tissue areas. Other particles - protons, alpha particles, neutrons - are used much less frequently in accordance with the characteristics and nature of the disease. The main disadvantage of existing methods used in radiation therapy is the lack of sufficient selectivity of the effect of radiation on malignant tumors. When exposed to ionizing radiation, both healthy and damaged tissues are affected, especially in cases where the tumor has a complex shape or is located in several places. An alternative for the treatment of such diseases may be neutron therapy, in particular neutron capture therapy.

In 1936, Gordon Locher hasproposed the concept of neutron capture therapy (NCT) [1]. It was proposed to inject boron, lithium, or gadolinium compounds into the cancerous tumor, followed by irradiation with slow neutrons. NCT was originally intended to be used to treat brain tumors. However, the results obtained over the past 10-15 years have shown new opportunities for the use of neutron capture therapy, in particular for the treatment of melanoma. Clinical studies have shown [2-4] that NCT may be an effective treatment for many other diseases, such as cancer of the colon and rectum, prostate, breast, lung, oral cavity, thyroid gland and other. Thus, modern technologies using neutrons are one of the most effective methods of treatment malignant tumors, therefore the need for sources of thermal neutrons with energy $E<0.5$ eV, epithermal in the energy range $0.5\ \text{eV}<E<10$ keV and fast neutrons $E> 10$ keV in the world are continuously growing.

For many years, traditional neutron sources based on nuclear reactors [2-5] and charged particle accelerators, including neutron sources with a subcritical assembly controlled by a pulsed electron accelerator beam, have been and are still being used for neutron and neutron capture therapy [6,7]. The removal of neutrons from the core of such sources is usually carried out using a neutron channel on which a slow-neutron beam former was installed.

To generate therapeutic neutrons for neutron capture therapy application, we have developed concept proposes to use delayed fission neutrons [8,9]. They can be formed under high-power electron beam interaction with a combined target from a tungsten and uranium dioxide. Under the photo- neutron interaction with uranium dioxide, a fission

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reaction is taken place, as a result, both prompt and delayed fission neutrons are emitted. The number of delayed neutrons is about 1% of the total number of produced ones. If we move a target activated in this way several tens of meters into a neutron flux generation system consisting of a heater, protection, collimator and reflector, we will obtain a compact neutron source for nuclear medicine. A significant advantage of such a neutron source is the absence of gamma background from the electron accelerator and the combined target, and a bulky protection system is not required.

The scheme of activated target transportation is shown in Figure 1. Activated targets are delivered to the shaper using a conveyor. As a result, concentrated flux of therapeutic neutrons is formed on the irradiated object. After the emission of delayed neutrons in the shaper, the uranium dioxide targets are returned to the core of the electron accelerator for reactivation. Thus, targets are transported cyclically as many times as necessary to reach a therapeutic dose when the object is irradiated. Proposed construction of the shaper is presented in Figure 2 in detail.

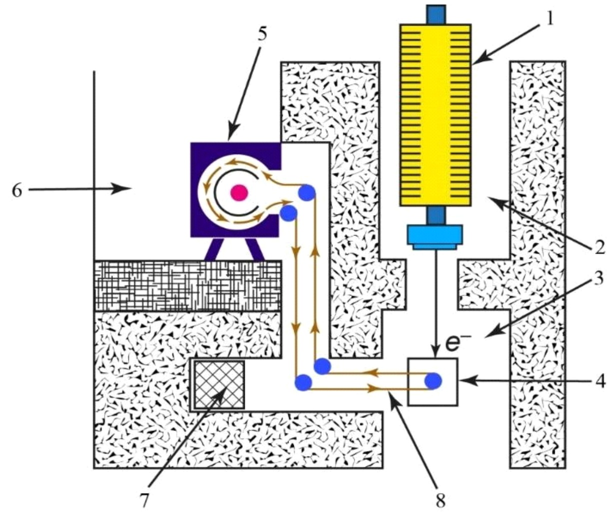

Figure 1. View of system for transporting activated targets: 1 - Electron accelerator; 2, 3 – Accelerator bunker; 4 – Active zone; 5 – Shaper; 6 – Radiation therapy room;7 – Radioactive waste repository; 8 – Conveyor

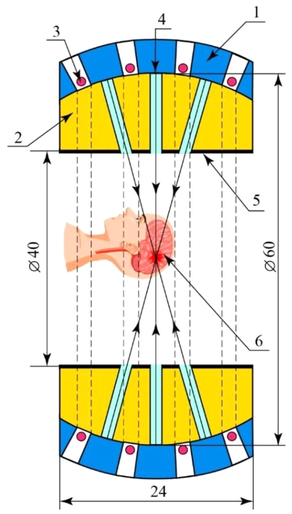

Figure 2. The design of the shaper of the concentrated therapeutic neutron flux (without a graphite reflector): 1 – Moderator; 2 - Radiation protection; 3 – Activated target; 4 – Channel of collimator; 5 – Cadmium layer; 6 – Irradiated object. All dimensions are in cm

After activation is completed, the target delivered to the shaper emits delayed fission neutrons with an average energy of 0.5 MeV, as well as gamma rays caused by induced radioactivity in the target. The radiation is isotropically distributed in all directions, including the direction of the irradiated object. Delayed neutrons passing through the moderator (1) change their energy close to epithermal range value (from 0.5 eV to 10 keV). They are directed to a therapeutic beam formed and focused by multi collimator system to the irradiated object located in the center of the shaper. To suppress induced gamma radiation and fast neutrons from the source in the direction of the irradiated object, combined blocking protection is provided.

DESCRIPTION OF THE COMPUTER MODEL OF THE CELL OF THE SYSTEM FOR FORMING CONCENTRATED SLOW NEUTRON FLUXES

In the work, a computer model of the cell of the system for generating concentrated slow neutron fluxes on delayed fission neutrons for nuclear medicine was developed in the Geant4 and PhysList QGSP BERT HP [10]. The hadronic part of this physics list consists of elastic, inelastic, capture and fission processes. Each process is built from a set of cross section sets and interaction models which provide the detailed physics implementation. The scheme of model the basic cell of the system for generating concentrated slow neutron fluxes is shown in Figure 3.

The basic cell, presented in Figure 3 comprises the two-point isotropic neutron sources (activated samples with uranium) with an energy of 0.5 MeV (1), a polyethylene neutron moderanor (2), a protective layer of borated polyethylene 10 cm thick to reduce the flux of fast neutrons (3), a neutron detector with an area of 1 см^2 (4).

The computer model of basic cell of the neutron source is presented in Figure 4. Using a computer model, a series of experiments was carried out with 10^7 neutrons per source. In the work we investigated the change in the number of neutrons hitting on the detector when the size of the moderator is changed. This dependence is presented in Figure 5. As can be seen from the Figure5, the optimal size of a cubic moderator from the point of view of the formation of therapeutic neutron fluxes is 3-4 cm.

In the work also we also determine the dependence of the number of neutrons that enter the detector on the position of the sources relative to the moderator and protection made of borated polyethylene. It is presented in Figure 6. From Figure 6 it can be seen that the optimal location of neutron sources is the angle formed by the edge of the moderator and the plane of protection made of borated polyethylene. That is, close to the moderator and protection made of borated polyethylene.

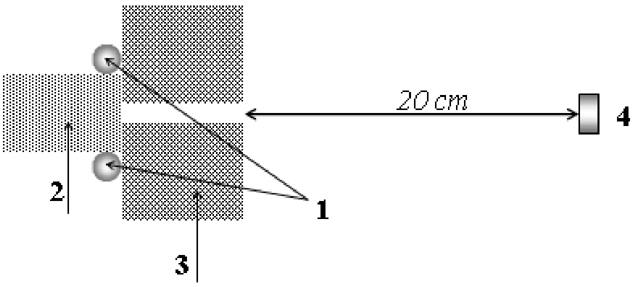

Figure 3. The basic cell of the neutron source
1-The two-point isotropic neutron sources (activated samples with uranium) with an energy of 0.5 MeV, 2- Polyethylene neutron moderator, 3- The protective layer of borated polyethylene 10 cm, 4- Thea neutron detector with an area of 1 см^2

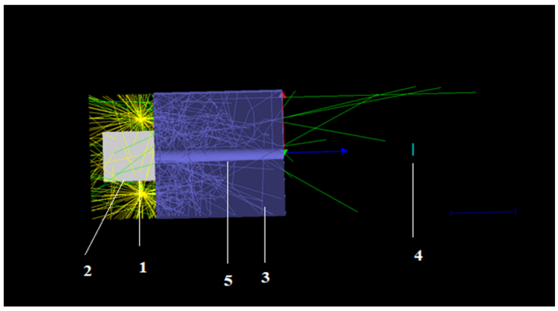

Figure 4. The computer model of basic cell of the neutron source
1-The two-point isotropic neutron sources (activated samples with uranium) with an energy of 0.5 MeV, 2- Polyethylene neutron moderator, 3- The protective layer of borated polyethylene 10 cm, 4- The neutron detector with an area of 1 см^2, 5 - Collimator

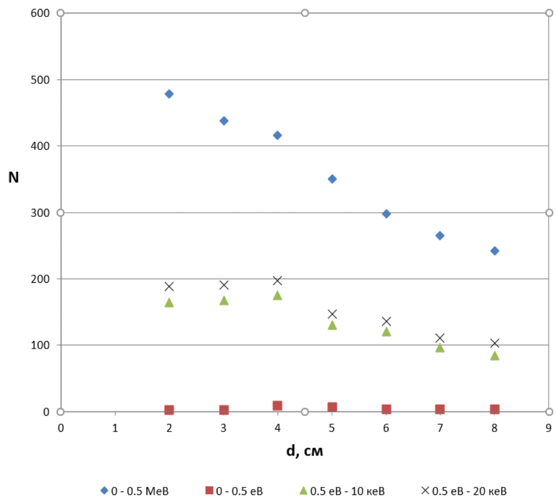

Figure 5. Dependence of the number of neutrons on the size of the moderator

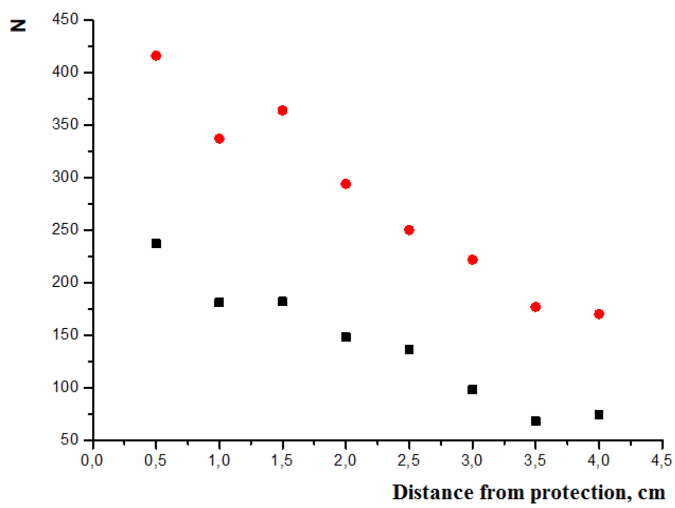

Figure 6. Dependence of the number of neutrons on the distance from protection

In the work we involved calculating the energy distribution of neutrons that enter the detector from the base cell of the shaper. The resulting spectrum is shown in Figure 7. The average statistical error was determined as the square root of the number of registered events. A study of neutron energy spectra showed that more than half of the neutrons whose fluxes are formed using such a cell of the formation system have an energy <100 keV, which is suitable for use for therapeutic purposes.

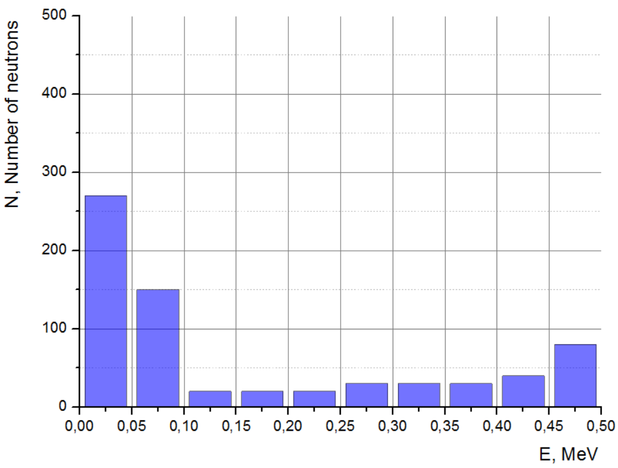

Figure 7. Neutron spectra from basic cell

In the process of working with a computer model based on the basic cell of the neutron flux generation system, a modernized cell was developed in order to increase the number of thermal neutrons that reach the detector. It differs from the basic cell in the reduced thickness of the polyethylene protection in front of the boron-free detector, the presence of a solid polyethylene moderator with holes for activated targets, as well as a 10 cm thick graphite reflector.

The modernized cell, presented in Figure 8 compries the two-point isotropic neutron sources (activated samples with uranium) with an energy of 0.5 MeV (1), a polyethylene neutron moderator (2), a protective layer of polyethylene without boron 5 cm thick (3), a neutron detector with an area of 1 см^2 (4), graphite reflector (5).

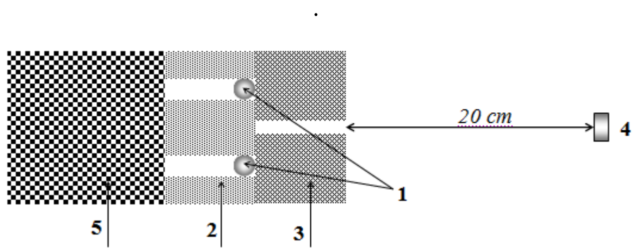

Figure 8. The modernized cell of the neutron source
1-The two-point isotropic neutron sources (activated samples with uranium) with an energy of 0.5 MeV, 2- Polyethylene neutron moderator, 3- The protective layer of polyethylene 5 cm, 4- neutron detector with an area of 1 см^2, graphite reflector

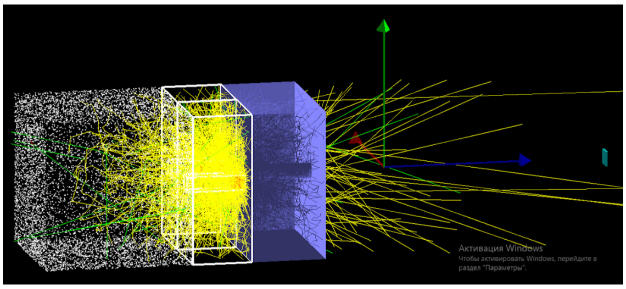

Figure 9. The computer model of modernized cell of the neutron source

In the work computer experiments using a model for a modified cell with 10^7 neutrons per neutron source were also carried out. Analysis of the data obtained showed that in this case the number of thermal neutrons hitting the detector increases 10 times compared to the base cell, and the energy of 80% of the particles does not exceed 5 keV, which is much better suited for therapeutic purposes. Neutron spectra are presented in Figure 10 and 11.

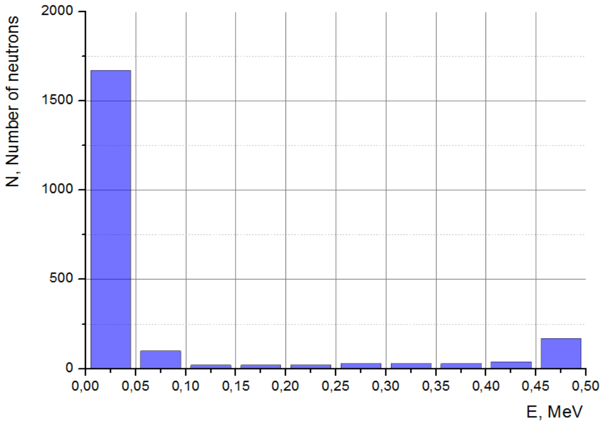

Figure 10. Neutron spectra from modernized cell

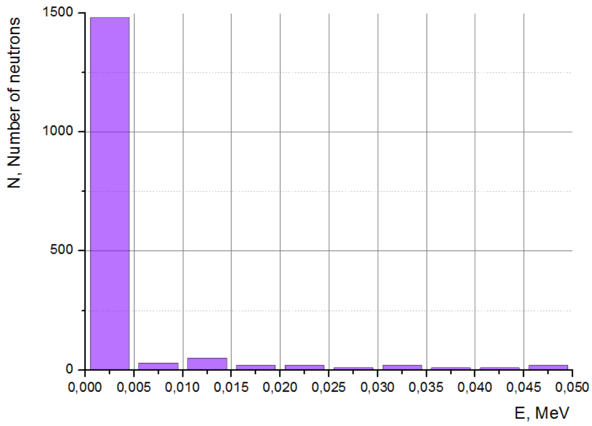

Figure 11. Neutron spectra from modernized cell, E <5 keV

CONCLUSIONS

In the work the computer model of a cell of a system for generating fluxes of therapeutic beams of delayed neutrons, based on the use of delayed fission neutrons, was developed in the Geant 4 environment. The basic cell of our neutron source consists of a cubic polyethylene moderator, fast neutron protection made of borated polyethylene with a conical collimator, a detector and two isotropic neutron sources with an energy of 0.5 MeV. A study of the dependence of the number of neutrons hitting the detector on the size of the moderator face showed that the optimal size would be 3-4 cm.

A study of neutron energy spectra showed that more than half of the neutrons whose fluxes are formed using such a cell of the formation system have an energy <100 keV, which is suitable for use for therapeutic purposes.

Analysis of the data obtained in a computer experiment made it possible to develop a modified cell of the system for generating streams of therapeutic beams of delayed neutrons, which differs from the basic one by the presence of a solid polyethylene moderator with holes for activated targets and a graphite reflector. Analysis of the data obtained showed that in this case the number of thermal neutrons hitting the detector increases 10 times compared to the base cell, and the energy of 80% of the particles does not exceed 5 keV, which is much better suited for therapeutic purposes. Thus, the computer model developed in the work of a cell of a system for generating flows of therapeutic slow-neutron beams allows not only to calculate the parameters of neutron flows incident on the detector, but also to improve the design of the device itself to obtain optimal characteristics for medical irradiation.

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REFERENCES

[1] G.L. Locher, Am. J. Roentgenol. Radium. Ther. **36**, 1 (1936). https://ia904501.us.archive.org/30/items/sim_ajr-american-journal-of-roentgenology_1936-07_36_1_0/sim_ajr-american-journal-of-roentgenology_1936-07_36_1_0.pdf

[2] A.M. Hughes, and N. Hu, Cancers, **15**(16), 4091 (2023). https://doi.org/10.3390/cancers15164091
[3] A. Wittig, and W.A.G. Sauerwein, Cancer Biother. Radiopharm. **38**(3), 195 (2023). https://doi.org/10.1089/cbr.2022.0074
[4] X. Cheng, F. Li, and L. Liang, Current Oncology, 29(10), 7868 (2022). https://doi.org/10.3390/curroncol29100622
[5] L.-W. Wang, Y.-W.H. Liu, and F.-I. Chou, Cancer Communications, **38**, 1 (2018). https://doi.org/10.1186/s40880-018-0295-y
[6] L. Porra, T. Seppälä, L. Wendland, H. Revitzer, H. Joensuu, P. Eide, H. Koivunoro, et al., Acta Oncologica, **61**(2), 269 (2021). https://doi.org/10.1080/0284186X.2021.1979646
[7] L. Porra, L. Wendland, T. Seppälä, H. Koivunoro, H. Revitzer, J. Tervonen, L. Kankaanranta, et al., Cancer Biother. Radiopharm. **38**(3), 184 (2023). https://doi.org/10.1089/cbr.2022.0059
[8] V. Kasilov, S. Gokov, S. Kalenik, S. Kochetov, L. Saliy, V. Tsyats'ko, E. Tsyats'ko, and O. Shopen, East European Journal of Physics, (4), 160-163 (2021). https://doi.org/10.26565/2312-4334-2021-4-21
[9] S.P. Gokov, S.H. Karpus, V.I. Kasilov, G.D. Kovalenko, and S.S. Kochetov, Problems of Atomic Science and Technology, **3**(145), 133 (2023). https://doi.org/10.46813/2023-145-133
[10] Geant4 Collaboration, Physics Reference Manual, https://geant4-userdoc.web.cern.ch/UsersGuides/ForApplicationDeveloper/BackupVersions/V10.6c/fo/BookForApplicationDevelopers.pdf

КОМП'ЮТЕРНА МОДЕЛЬ СИСТЕМИ ФОРМУВАННЯ ПОТОКІВ ТЕПЛОВИХ ЗАПІЗНИЛИХ НЕЙТРОНІВ ДЛЯ ЯДЕРНОЇ МЕДИЦИНИ

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В роботі в середовищі Geant 4 була розроблена комп'ютерна модель осередку системи формування потоків терапевтичних пучків сповільнених нейтронів, яка заснована на використанні запізнілих нейтронів поділу. Сутність такого джерела нейтронів полягає в тому, що при взаємодії потужного електронного пучка з комбінованою мішенню з вольфраму та мішенню яка містить подільний матеріал, відбувається реакція поділу; в результаті якої випромінюються нейтрони. Якщо перенести активовану таким чином мішень на декілька десятків метрів в систему формування потоків нейтронів, яка складається з отеплювача, захисту, коліматору та відбивача, ми отримаємо компактне джерело нейтронів для ядерної медицини. Вагомою перевагою такого джерела нейтронів є відсутність гама фону від прискорювача електронів та комбінованої мішені, при цьому буде непотрібна громіздка система захисту. В середовище Geant 4 була розроблена геометрія цього осередку та проведена низка експериментів на 10^7 нейтронів. При цьому використовувався фізичний лист QGSP BIC HP. Дослідження енергетичних спектрів нейтронів довело, що більше половини нейтронів, потоки яких формуються за допомогою такого осередку системи формування мають енергію < 20 кеВ, яка є придатною для використання в терапевтичних цілях. Аналіз отриманих в комп'ютерному експерименті даних дав можливість розробити модифікований осередок системи формування потоків терапевтичних пучків сповільнених нейтронів, який відрізняється від базового, наявністю цільного отеплювача з поліетилену з отворами для активованих мішеней, та відбивача з графіту. Аналіз отриманих даних довів, що в цьому разі кількість теплових нейтронів, які потрапляють на детектор зростає у 10 разів в порівнянні з базовим осередком, а енергія 80% частинок не перевищує 5 кеВ, що значно краще підходить для терапевтичних цілей.

Ключові слова: *терапевтичні пучки; запізнілі нейтрони; прискорювач електронів; комп'ютерна модель; нейтрон-захватна терапія*