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CONCEPT OF NEUTRON SOURCE CREATION FOR NUCLEAR MEDICINE BASED ON LINEAR ELECTRON ACCELERATOR†

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We review the current status of the development of sources of epithermal neutrons sources based on reactors and accelerators for boron neutron capture therapy (BNCT), a promising method of malignant tumor treatment. The scheme is proposed of the source prototype for the production of thermal and epithermal neutrons using the delayed neutrons generated with help of linear electron accelerator at the target containing the fissile material. The results of an experiment are presented in which the half-life curves of radioactive nuclei formed during fission and emitting delayed neutrons are measured. It is shown that an activated target containing fissile material is a compact small-sized source of delayed neutrons. It can be delivered to the shaper, where, using a moderator, an absorber, and a collimator, neutrons of thermal or epithermal energies are formed over a certain period of time, after which this target is sent to the activator, and another target comes in its place. Thus, a pulsed neutron flux is formed. Such a neutron beam can be used in nuclear medicine, in particular, in neutron capture therapy in the treatment of cancer. An important task in the implementation of neutron capture therapy, when irradiating patients, is to control both the intensity and the energy spectrum of the neutron flux. To solve this problem, an earlier developed activation-type neutron ball spectrometer can be used, which will allow optimization of various parameters of the shaper, collimator and filters in order to obtain the most powerful neutron fluxes.
Keywords: nuclear medicine, delayed neutrons, thermal neutrons, linear accelerator, neutron source
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CONCEPT OF NEUTRON CAPTURE THERAPY

Treatment of tumor by means of neutron capture therapy requires formatted beams of thermal or epithermal neutrons with the flux density (2-3) 10^9 neutron/(cm^2 s), which can be generated at different devices, namely, reactors and charged particle accelerators. The essence of the method consists in preliminary injection to the patient of medication containing ^{10}B or ^{157}Gd which are accumulated predominantly in the tumor.

When thermal or epithermal neutrons interact with the these elements reaction products are obtained. E.g., stable isotope ^{10}B transforms after absorbing the neutron into the excited nucleus ^{11}B which decays within 10^{-12} seconds into the kernel ^{7}Li and -particle having large energy (about 2 MeV). These charged particles are quickly slowed down within the cancer cell. 80 % of the energy is released in the same cell which contained the Boron kernel what leads to the distraction of this cell.

Up to now, nuclear reactor were the most convenient sources of thermal or epithermal neutrons for neutron capture therapy [1-5]. In such an installation, patient is located in a special box behind the biological protection which has a neutron channel for the output of the formatted beam of thermal or epithermal neutrons to the distances up to 3-5 m. This is due to the fact that neutron flux density is decreasing inversely with the square of distance, and this density at larger distances is not sufficient for the irradiation of the patient despite the high neutron flux in the active zone which is of the order of 10^{14}-10^{15} neutrons/cm^2. Unfortunately such installations cannot be used directly in clinics because this is a large scale, complex and very expensive equipment. Moreover, a trend appeared recently is to use in clinics compact sources of thermal or epithermal neutrons. E.g., a project of 10 kW reactor device «Mars» for the treatment of oncological deceases has been developed in Russia.

During the last decade, an increasing interest is seen to the creation of compact, relatively cheap straight flow accelerators which are capable to generate neutrons for neutron and neutron capture therapy directly at oncological centers [6-8]. Creation of the compact source of thermal and epithermal neutrons on the basis of linear electron accelerator is also an actual task. For this purpose, we have performed preliminary studies of the new method of neutron generation using a linear electron accelerator [6]. This method is based on the use of delayed fission neutrons which are released from the activated target containing the fissile material.

The purpose of the present work is the analysis of the results obtained earlier in the studies of the method [9] of generation of thermal and epithermal neutrons, and, based on these results, creation of the prototype of the compact source on the basis of linear electron accelerator LINAC-300. This source can be a prototype for the full scale source of thermal and epithermal neutrons, which can be built on the basis of existing at NSC KIPT linear accelerator with 20 kW power in the outgoing electron beam. This allows to generate necessary neutron fluxes for the use in nuclear medicine.

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METHOD OF GENERATION OF THERMAL AND EPITHERMAL NEUTRONS USING THE LINEAR ELECTRON ACCELERATOR

Usually generation of neutrons with help of the linear electron accelerator uses the outgoing beam with the energy 20 MeV at the target from the heavy material. In this work, it is proposed to use a target containing the fissile material ^{238}U with 2% enrichment with ^{235}U and with the volume of 1 cm^3 located in the activator on exit from the electron accelerator.

Activator consists of the moderator and reflector which are needed for the creation of the field of thermal neutrons. These neutrons are produced as a result of slowing down of delayed fast neutrons appearing in process of interaction of the electron beam with the target consisting of fissile material.

It is known that the interaction of electron beam with the target of fissile material leads to the generation of γ -quanta and photo-neutrons which stimulate nuclear fission reaction with formation of derbies. Photo-fission reaction results in instantaneous as well as in delayed neutron generation. Relative contribution of delayed neutrons is 1% of all neutrons.

Group parameters [10] of delayed neutrons in case of ^{235}U fission by the thermal neutrons are presented in Table.

Group	Relative contribution $a_i \pm \Delta a_i$	Half-decay period $T_i \pm \Delta T_i$
1	0.038 ± 0.001	53.95 ± 0.028
2	0.211 ± 0.004	22.34 ± 0.13
3	0.197 ± 0.004	6.40 ± 0.08
4	0.396 ± 0.005	2.26 ± 0.03
5	0.132 ± 0.004	0.494 ± 0.017
6	0.026 ± 0.001	0.179 ± 0.006

As seen from Table 1, half-decay periods change depending on the group from hundreds of milliseconds to 54 seconds. Note that after activation of the target containing fissile material by the electron beam and by the field of thermal neutrons formed in the activator, target becomes a compact source of delayed neutrons. Such a target can be transported during 1-2 s to the distance of 20-50 m from the active zone of the accelerator to the device-formator located in a different room. It is seen from Table 1 that the main contribution to the emission of delayed neutrons is made by groups 2,3 and 4. First group contributes less than 4% while 5 and 6 groups give practically no contribution because of a short half-decay period as compared to the transportation time of the activated target to the formator where it emits delayed neutrons. Device-formator consists of the moderator, reflector, filter, absorber and collimator which are needed for the achievement of neutron beam parameters necessary for the neutron capture therapy of oncological diseases.

Based on the above conclusions one can propose a principal scheme of the prototype of the device for the generation of thermal or epithermal neutrons. This scheme is shown in Fig.1 where it is seen that one can use two-path pneumatic mail connecting the activator of target and the formator of thermal and epithermal neutrons.

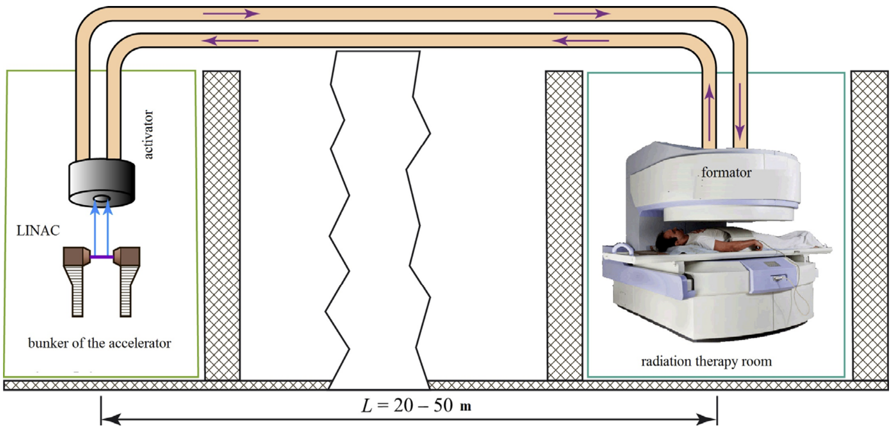

Figure 1. Principal scheme of the prototype of the device for the generation of thermal or epithermal neutrons

We suppose that system shown schematically in Fig.1 uses two targets. One is currently located in the activator where it is activated by the electron beam and the other one is located in the block-formator where it emits delayed neutrons during a certain time period. When time of presence in the formator emitting delayed neutrons is over targets are exchanged with help of pneumatic mail. Such a procedure can be repeated as many times as needed for the accumulation of the therapeutic dose at irradiated object. The activated target is a compact source of delayed neutrons which can be moved during the time about 1-2 s to the formator located near the irradiated object at the distance of 20-50 m from the activator.

In the earlier studies [9], we have measured decay curves for delayed neutrons released from the activated target and converted by the formator into thermal and epithermal neutrons. The results of the measurements are presented in Fig. 2.

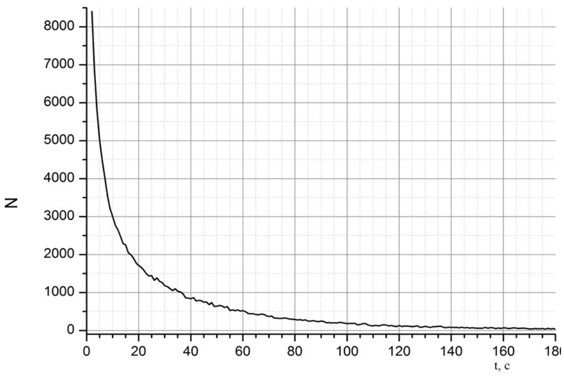

Figure 2. Decay curve of delayed neutrons slowed down to the energies in the range from 0.5 eV to 10 keV.

After the procession of the decay curve presented in Fig. 2, the dependence of the average flux density of slowed down neutrons at the supposed object on the emission time from the activated target in the device-formator has been obtained. The results of data procession are presented in the form of the histogram in Fig.3.

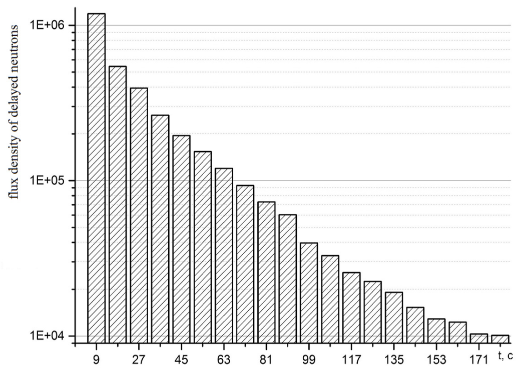

Figure 3. Flux density of delayed neutrons as function of time of emission in the device-formator (in the logarithmic scale)

It is seen from the figure that flux density of delayed neutrons decays exponentially with emission time of delayed neutrons by the sample activated in the device-formator. E.g., the shorter is the emission time interval the higher is the delayed neutron flux. Thus, if two targets are used which are subsequently exchanged with help of pneumatic mail between the activator and formator as shown in Fig.1, the procedure described above can be used for the creation of the so called pulsed source of thermal and epithermal neutrons. Then the duration of neutron pulse will be determined by the time of presence of the activated target in the formator, and the distance between pulses will be determined by the transportation time of the activated target to the formator. After slowing down of delayed neutrons and their passage through the filters, absorbers and collimator we obtain the neutron beam with necessary parameters for the neutron capture therapy. The dose achieved will be determined by the number of pulses of thermal or epithermal neutrons. As shown in [6], such a neutron beam can be created on the basis of a linear electron accelerator.

An important task in the implementation of neutron capture therapy, when irradiating patients, is to control both the intensity and the energy spectrum of the neutron flux. To solve this problem, an earlier developed spherical neutron spectrometer of activation type can be used [11]. The neutron spectrometer will also allow optimization of various parameters of the formator, collimator and filters in order to obtain the most powerful neutron fluxes that would meet the requirements of neutron capture therapy.

CONCLUSIONS

A scheme of the prototype of the compact neutron source has been proposed on the basis of the new method for the generation of thermal and epithermal neutrons with help of linear electron accelerator using delayed neutrons from the activated target containing fissile material. This prototype can be used for the development of the full-scale neutron source for neutron and neutron capture therapy of oncological diseases.

It has been also shown that the use of the above method for the generation of thermal and epithermal neutrons allows to create compact neutron sources on the basis of linear electron accelerators. Development of such sources opens the prospects to place them directly at the territory of clinic, to carry out the treatment of oncological patients and to create at operating accelerators of the radiation therapy cabinets.

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КОНЦЕПЦІЯ СТВОРЕННЯ ДЖЕРЕЛА НЕЙТРОНІВ ДЛЯ ЯДЕРНОЇ МЕДИЦИНИ НА ОСНОВІ ЛІНІЙНОГО ПРИСКОРЮВАЧА ЕЛЕКТРОНІВ

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Розглянуто сучасний стан розробки джерел епітеплових нейтронів на базі реакторів та прискорювачів для бор-нейтронозахватної терапії (БНЗТ), перспективного методу лікування злоякісних пухлин. Запропоновано схему прототипу джерела для отримання теплових і епітеплових нейтронів з використанням запізнілих нейтронів, що генеруються за допомогою лінійного прискорювача електронів на мішені, що містить подільний матеріал. Наводяться результати експерименту, в якому виміряні криві напіврозпаду радіоактивних ядер, що утворилися в процесі поділу і випускають запізнілі нейтрони. Показано, що активована мішень, що містить подільний матеріал є компактним малогабаритним джерелом запізнілих нейтронів. Вона може бути доставлена в формувач, де за допомогою сповільнювача, поглинача і коліматора відбувається формування нейтронів теплових або епітеплових енергій протягом певного проміжку часу, після чого ця мішень відправляється в активатор, а на її місце приходить інша. Таким чином, утворюється імпульсний потік нейтронів. Такий пучок нейтронів може бути використаний в ядерній медицині, зокрема, в нейтронозахватної терапії при лікуванні онкологічних захворювань. Важливим завданням при реалізації нейтронозахватної терапії, при опроміненні пацієнтів, є проведення контролю, як інтенсивності так і енергетичного спектра потоку нейтронів. Для вирішення цього завдання може бути використаний раннє розроблений кульовий спектрометр нейтронів активаційного типу, який дозволить провести оптимізацію різних параметрів формувача, коліматора і фільтрів з метою отримання найбільш потужних потоків нейтронів.

Ключові слова: ядерна медицина, запізнілі нейтрони, теплові нейтрони, лінійний прискорювач електронів, джерело нейтронів