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^{124}Sb–Be photo-neutron source for BNCT: Is it possible?

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A B S T R A C T

In this research a computational feasibility study has been done on the use of ^{124}SbBe photo-neutron source for Boron Neutron Capture Therapy (BNCT) using MCNPX Monte Carlo code. For this purpose, a special beam shaping assembly has been designed to provide an appropriate epithermal neutron beam suitable for BNCT. The final result shows that using 150 kCi of ^{124}Sb, the epithermal neutron flux at the designed beam exit is 0.23×10^9 (n/cm^2 s). In-phantom dose analysis indicates that treatment time for a brain tumor is about 40 min which is a reasonable time. This high activity ^{124}Sb could be achieved using three 50 kCi rods of ^{124}Sb which can be produced in a research reactor. It is clear, that as this activity is several hundred times the activity of a typical cobalt radiotherapy source, issues related to handling, safety and security must be addressed.

1. Introduction

Boron Neutron Capture Therapy (BNCT) is a method of radiation therapy which originally was developed for malignant brain tumors [1]. This method is based on the irradiation of boron-containing tumor cells by an appropriate neutron beam. Lethal doses deposited by the ^{10}B(n,α)^{7}Li reaction products cause destruction of the tumor cells. The qualified neutron beam for this purpose is determined by the International Atomic Energy Agency (IAEA). Table 1 shows the recommended parameters for neutron beams [2].

In order to provide an appropriate neutron beam, a Beam Shaping Assembly (BSA) must be designed based on the neutron source specifications. All clinical trials were performed using nuclear research reactors [2] but this kind of neutron source has social acceptance problem. At present, major efforts are underway to develop a non-reactor neutron source for BNCT. These efforts are focused on the use of particle accelerators [7,8]. Another kind of neutron source is the ^{252}Cf radioisotope. It was reported that for BNCT application a source of the order 1 g of ^{252}Cf would be needed, which would be very difficult to obtain [2] thus actually it is impossible to produce the BNCT facility by ^{252}Cf with an intense enough neutron beam to get a reasonable irradiation time. This paper presents a computational feasibility study on the use of ^{124}SbBe photo-neutron source for BNCT. This neutron source has two important advantages: (1) the source has effectively an on/off switching capability since the removal of the Be target would terminate the production of the neutrons; (2) it emits neutrons with a mean energy of ~24 keV. These neutrons can easily moderate to the epithermal neutron energy range which is suitable for BNCT. The main disadvantage of the source is its short half-life; however, it is always possible to “charge” the source up again by irradiation in a nuclear reactor. This source is used as a portable neutron radiography system [9].

The transportable and rechargeable features of this neutron source motivate us to investigate the possibility of BNCT applications.

2. Materials and methods

A typical ^{124}Sb source has been considered as reported by Fantidis et al. [9] and then the optimum thickness of the Be target has been selected. After this, a BSA has been proposed to achieve an appropriate neutron beam for BNCT. Finally, in-phantom parameters have been calculated and compared with some other BNCT neutron beams. All calculations have been performed using MCNPX Monte Carlo code [10].

2.1. The ^{124}Sb–Be neutron source

In the ^{124}SbBe neutron source, neutrons are formed from the interaction of the photons emitted from ^{124}Sb ($t_{1/2}=60.2$ days, $E_\gamma = 1.691$ MeV, transition probability = 47.1%) with the Be through the photo-neutron reaction ^{9}Be (γ, n)^{8}Be. Gryaznykh et al. [11] show that the photo-neutron yield for ^{9}Be target is given by Eq. (1):

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Table 1
The final neutron beam parameters.

Facility	φ_{epi} $\left(10^9 \frac{\text{n}}{\text{cm}^2\,\text{s}}\right)$	$\frac{\varphi_{epi}}{\varphi_{thermal}}$	$\frac{D_{fast}}{\varphi_{epi}}$ $(10^{-13}\ \text{Gy cm}^2)$	$\frac{D_{gamma}}{\varphi_{epi}}$ $(10^{-13}\ \text{Gy cm}^2)$
IAEA [2]	0.5–1	>20	<2	<2
THOR [3]	1.69	N/A	2.8	1.25
FiR-1 [4]	1.2	N/A	3.3	0.9
TRR [5]	0.65	25	2.2	2.1
Isfahan MNSR [6]	0.635	N/A	0.07	0.87
Syrian MNSR [15]	0.28	N/A	7.98	1.7
^{124}Sb–Be	0.23	45	0.49	0.55

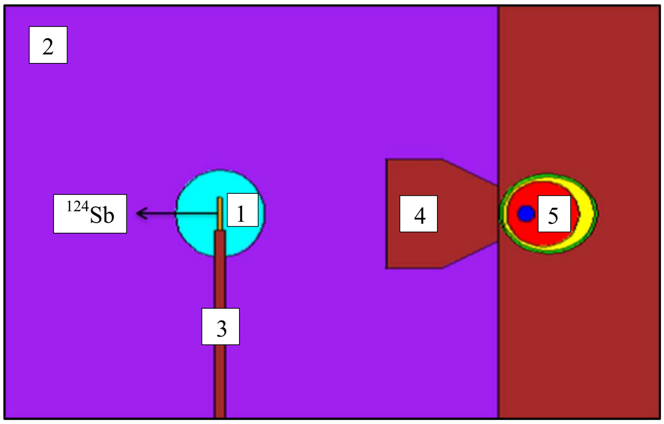

Fig. 1. The final geometry which is modeled in MCNPX code: 1) Be target, 2) Pb, 3) ^{124}Sb guide tube to the shield, 4) collimator, 5) Snyder head phantom.

$$w(E) = \frac{\sigma_{\gamma n}(E)}{\sigma_{total}(E)}\left(1 - \exp\left(\sigma_{total}(E)\rho d\right)\right) \tag{1}$$

where $w(E)$ is the neutron yield per gamma quanta emitted from the antimony source, $\sigma_{\gamma n}$ is the photo-neutron production cross section, σ_{tot} is the total photon scattering and absorption cross section, ρ is the target density and d is the target thickness. As the neutron yield is dependent on the Be thickness, configurations of different thickness of the Be have been analyzed. The ^{124}Sb part of the source was simulated as a vertical cylinder with 0.42 cm in radius and 6 cm in height which, was located at the center of a spherical Be, as shown in Fig. 1. The activity of the ^{124}Sb has been assumed to be equal to 1.85×10^{13} Bq (=500 Ci) [9]. The neutron energy, E_n, produced by the ^{9}Be $(\gamma, n)^8$Be reaction has been defined as follows [12]:

$$En(\theta) \cong \frac{M(E\gamma + Q)}{m + M} + \frac{E\gamma\left[(2Mm)(M + m)(E\gamma + Q)\right]^{1/2}}{(m + m)^2}\cos(\theta) \tag{2}$$

where θ is the angle between the gamma ray and neutron emission, $E\gamma$ is gamma energy, Q is the Q-value of ^{9}Be $(\gamma, n)^8$Be reaction and M and m are the rest mass energy of Be and neutron respectively.

The goals of this step were to achieve minimum mean neutron energy (E_n), maximum number of neutrons (N_n) and minimum number of photons (N_p) on the Be outer surface. To reach these goals, three parameters have been defined and calculated in each trial which were E_n, N_n/E_n and N_n/N_p. The best thickness of the Be is the one which provide the highest value of N_n/E_n and N_n/N_p and the lowest value of E_n.

2.2. Neutron beam design

After selecting the best Be thickness, the BSA has been designed. The BSA consists of moderator, reflector, gamma filter and thermal neutron filter. As the gamma dose is high and the neutron energy is low, Pb has been considered for neutron moderator, neutron reflector and gamma filter. The collimator has been assumed as an air filled incomplete cone. Fig. 1 shows the final geometry which is modeled in MCNP code. The goal of this phase is to achieve the IAEA recommended values for the neutron beam parameters (Table 1). F4/E4 MCNP cards have been used to calculate three-group neutron flux and F6/E6 cards to calculate gamma and fast neutron dose. Different configurations and thicknesses have been tested. The best configuration is illustrated in Fig. 1.

2.3. In-phantom parameters

To evaluate the final beam performance, In-phantom parameters have been calculated. These parameters are [2]: Therapeutic Gain (TG), namely the total tumor dose to maximum normal brain dose; Advantage Depth Dose Rate (ADDR), namely the maximum normal brain dose; Advantage Depth (AD), namely the depth at which the dose to the tumor equals the maximum dose to the normal brain dose and Therapeutic Depth (TD), namely the depth at which the dose to the tumor equals twice the maximum dose to the normal brain dose. These parameters have been calculated using the Snyder head phantom [13] as shown in Fig. 2. A sphere with radius 1.5 cm in depth of 3.5 cm in the brain has been considered as a brain tumor. The boron concentration has been assumed to be 18 and 65 ppm in normal brain and tumor respectively [5]. In BNCT, the total dose is the weighted sum of the four absorbed dose components originating from the neutron and gamma interactions in tissues [2]:

$$D_{\text{total}}(\text{Gy–eq}) = w_g D_g + w_f D_f + w_N D_N + w_B D_B \tag{3}$$

where D_g is the absorbed dose due to gamma rays, D_f is the absorbed dose due to ^{1}H (n, n)^{1}H reaction, D_N is the absorbed dose due to ^{14}N(n, p)^{14}C reaction, D_B is the absorbed dose due to ^{10}B(n,α)^{7}Li reaction and w_g=1, w_f=3.2, w_N=3.2 and w_B=1.38 for

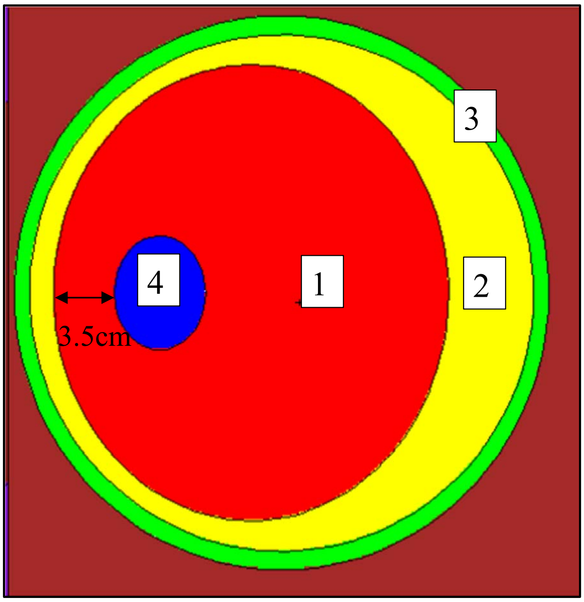

Fig. 2. The MCNPX model of the Snyder head phantom: 1) brain, 2) skull, 3) skin, 4) tumor.