



Assembly Neutron Moderation System for BNCT Based on a ^{252}Cf Neutron Source

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In this paper, a neutron moderation system for boron neutron capture therapy (BNCT) based on a ^{252}Cf neutron source is proposed. Different materials have been studied in order to produce a high percentage of epithermal neutrons. A moderator with a construction mixture of AlF_3 and Al, three reflectors of Al_2O_3 , BeO, graphite, and seven filters (Bi, Cu, Fe, Pb, Ti, a two-layer filter of Ti+Bi, and a two-layer filter of Ti+Pb) is considered. The MCNPX simulation code has been used to calculate the neutron and gamma flux at the output window of the neutronic system. The results show that the epithermal neutron flux is relatively high for four filters: Ti+Pb, Ti+Bi, Bi, and Ti. However, a layer of Ti cannot reduce the contribution of γ -rays at the output window. Although the neutron spectra filtered by the Ti+Bi and Ti+Pb overlap, a large fraction of neutrons (74.95%) has epithermal energy when the Ti+Pb is used as a filter. However, the percentages of the fast and thermal neutrons are 25% and 0.5%, respectively. The Bi layer provides a relatively low epithermal neutron flux. Moreover, an assembly configuration of 30% AlF_3 +70% Al moderator/ Al_2O_3 reflector/a two-layer filter of Ti+Pb reduces the fast neutron flux at the output port much more than other assembly combinations. In comparison with a recent model suggested by Ghassoun et al., the proposed neutron moderation system provides a higher epithermal flux with a relatively low contamination of gamma rays.

Keywords: Epithermal neutron beam, Gamma ray contamination, MCNPX, BNCT, Neutron moderation system

Introduction

Clinical trials of boron neutron capture therapy (BNCT), on-going in the United States (US), Europe and Japan, will evaluate the safety and efficacy of this modality in the treatment of human tumors. These trials should prove successful, the development of BNCT into a routine therapeutic modality will then depend, in part, on the availability of suitable neutron generators/sources that are compatible with installation in a hospital environment.

At present, the clinical trials of BNCT are being per-

formed at research nuclear reactor facilities. However, this paper deals with the generation of epithermal neutron fields with radioactive neutron sources for the treatment of tumors using BNCT. Such sources offer a number of potential advantages over either reactor or accelerator-based neutron generators for clinical applications. First, radioactive neutron sources can be easily embedded in neutron moderation system when the neutron field is required. This, and the fact that neutrons are not produced via a critical assembly of fissile material, means that licensing and regulations associated with maintaining the

neutron source are substantially simplified. Second, the capital expenses of a radioactive neutron source based on BNCT system will be substantially lower than those associated with installation of a reactor or an accelerator system in or near a hospital. It is likely that capsule hardware for BNCT irradiations could be sited within a suitable corner of radiotherapy room with the addition of extra shielding. Third, heat removal systems are not required. Fourth, there is a better economics for third world countries that have no suitable reactors and accelerator facilities.

A radioactive neutron source for BNCT is composed of a number of components: (i) an appropriate neutron-producing source, and (ii) a moderator/reflector/filter assembly to render the flux energy spectrum of neutrons produced in the target suitable for patient irradiation. BNCT may be a suitable treatment for a number of tumor types. If the tumor is located such that neutrons can be suitably delivered, and it is of a type which takes up a boronated drug, then treatment may be possible. In addition, in common with all other radical radiotherapy treatments, local control of the primary tumor should be the principal clinical problem. There are a number of tumors for which these factors apply, but the majority of interest world-wide has focused on glioblastoma multiforme,¹⁾ metastatic melanoma,²⁾ and liver³⁾ tumors. BNCT is a form of binary radiotherapy and therefore involves two key stages. The first is the preferential accumulation, in tumor cells, of ^{10}B isotope with a suitable affinity for neutrons at a certain energy. Second, this must then be followed by an intense irradiation of these cells with neutrons at energy such that their probability for capture is maximized. The heavy particles of Lithium isotope of ^7Li and Helium isotope of α , produced via the nuclear reaction $^{10}\text{B}(n,\alpha)^7\text{Li}$, have high linear energy transfer (LET) and high relative biological effectiveness (RBE).⁴⁾ These particles deposit the energy about 2.34 MeV locally in very short path-lengths in tissues (5~9 μm), which corresponds to the cell diameters.⁴⁾ In general in BNCT, a high neutron flux is required in order to achieve high sensitivities. In this regard, the obvious choices are facilities based on either reactor or accelerator.⁵⁾ However, by the reasons of the mentioned above, radioactive neutron sources may provide a good alternative. The radioisotope of ^{252}Cf ($T_{1/2}=2.645$ years) is one of the best neutron source for this

purpose.⁶⁾ It is used extensively in research, industry and medicine. One milligram of ^{252}Cf emits approximately 2×10^9 neutrons per second.

We have the goal to propose a neutron moderation system in order to obtain the maximum possible epithermal neutron flux between ~ 0.5 eV~10 keV. In Sec. 2, we give a MCNP model for describing the proposed neutronic system. We evaluate different materials and geometry configurations. In Sec. 3, the results and discussion are given. For future experiments we suggest the best parameters of our simulations. Finally, conclusions are given in the last section.

Materials and Methods

In order to make a neutron beam available for the treatment of deep tumor with BNCT, large fractions of epithermal neutrons with the energy range of 0.5eV-10keV are required. In this work, a neutron moderation system shaped to produce suitable epithermal neutron beam for BNCT brain tumor treatments with minimal contributions of fast and thermal neutrons and gamma (γ) rays, is proposed. Three major components are the moderator, the reflector, and the γ -filter. A MCNP model of these components has been shown in Fig. 1.

The basic configuration of this system comprises a cylindrical ^{252}Cf source, localized at the central axis at the end of a cylindrical moderator. The moderator contains 30% AlF_3 and 70% Al . After the choice of the moderator, we have simulated some of reflector materials such as Al_2O_3 , BeO

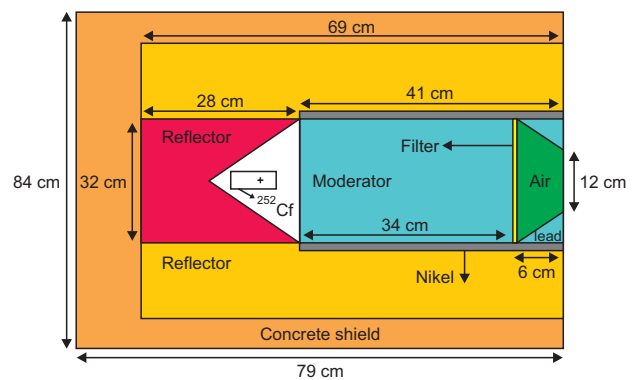


Fig. 1. A MCNP geometrical scheme of the proposed neutron moderation system.

and graphite. The moderator has been covered by a layer of Nickel (Ni) due to very low neutron moderation and low contamination of γ -rays. For more reduction of γ -rays at the output port of the system, we have examined different γ -filters with different thicknesses. The transmitted flux have been calculated for Lead (Pb), Bismuth (Bi), Iron (Fe), Copper (Cu), Titanium (Ti), a two layer of Ti+Pb, and a two layer of Ti+Bi.

Results

The curves given in Fig. 2 show that Al_2O_3 is the best reflector comparatively. Several filter materials have been investigated in order to reduce contributions of γ -rays and fast and thermal neutrons. Fig. 3 shows the obtained en-

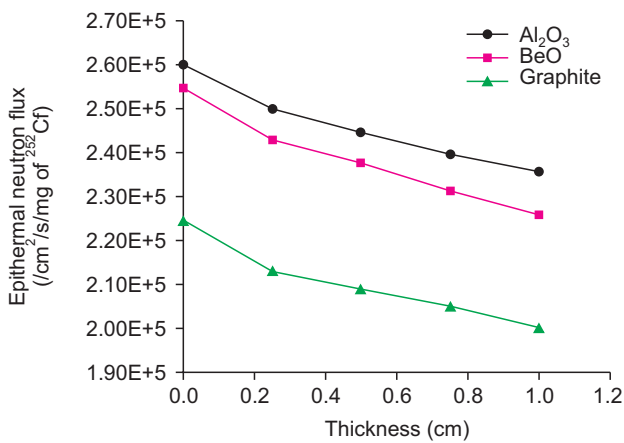


Fig. 2. Total epithermal neutron flux versus the size of the two layer filter of Ti+Pb with different reflectors.

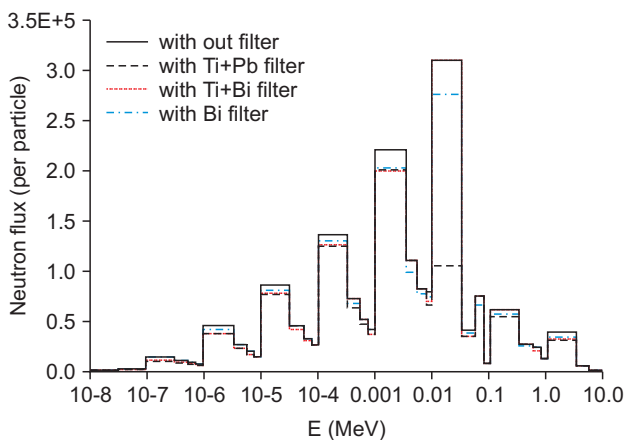


Fig. 3. Neutron energy spectra at the output port of the proposed neutron moderation system.

ergy spectra at the output port of the neutron moderation system for different filters. Fig. 4 shows dependency of the epithermal neutron flux on the filter size. Fig. 4 indicates that the epithermal neutron flux is relatively high for the four filters Ti+Pb, Ti+Bi, Bi, and Ti. Fig. 5 has been plotted for the total γ flux versus filter size. It shows that a layer of Ti cannot reduce the contribution of γ -rays at the output window. Table 1 illustrates the percentage of neutron flux produced by different filters. As shown in Fig. 3, although the energy spectra filtered by Ti+Bi and Ti+Pb overlap very

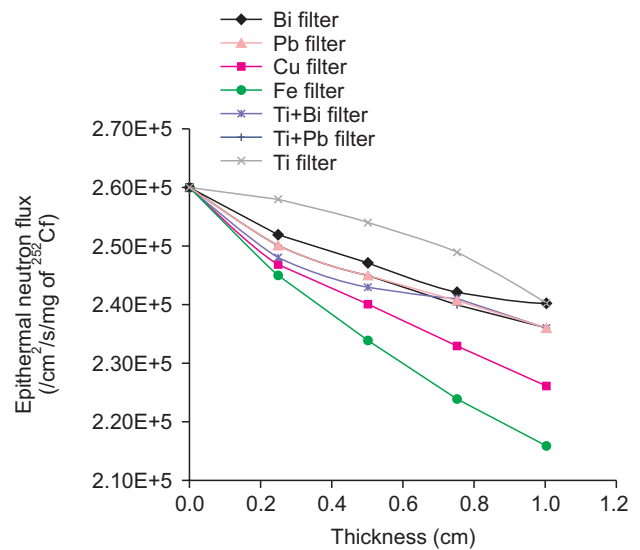


Fig. 4. Total epithermal neutron flux versus filter thickness.

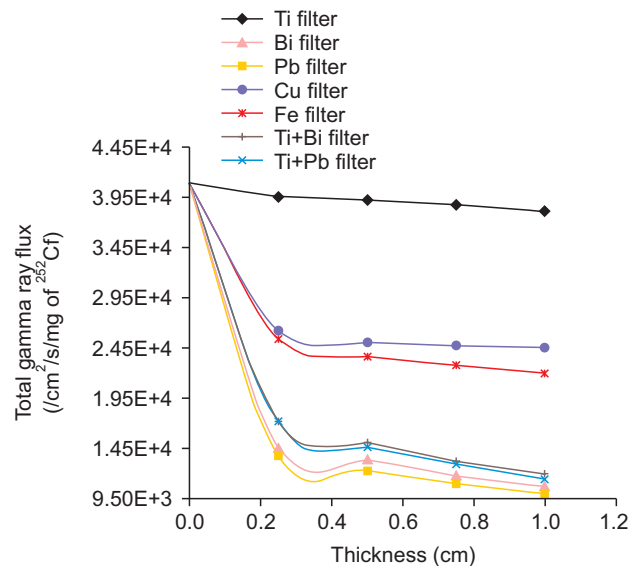


Fig. 5. Total flux of γ -rays versus filter thickness.

Table 1. The percentage of neutron flux produced using different filters.

Filter	Ti	Pb	Cu	Fe	Bi	Ti+Bi	Ti+Pb
Thermal flux	1.06	1.35	0.96	1.05	1.35	1.10	0.05
Epithermal flux	73.39	64.32	65.54	63.02	64.56	74.00	74.95
Fast flux	25.55	34.33	33.50	35.93	33.99	24.90	25.00

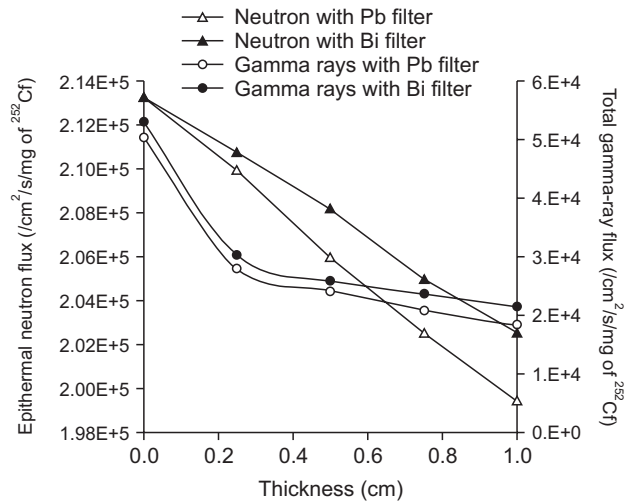
well, but Table 1 shows that a higher percentage of neutrons (74.95%) take the epithermal energy using a two layer filter of Ti+Pb. However, the percentages of the fast and thermal neutrons are 25% and 0.5%, respectively.

Discussion

In order to produce a big percentage of epithermal neutrons we have proposed an alternative model of a neutron moderation system for BNCT based on a ^{252}Cf neutron source. We have considered a moderator with a construction of AlF_3 and Al, three reflectors of Al_2O_3 , BeO, Graphite and seven filters of Bi, Cu, Fe, Pb, Ti, a two layer filter of Ti+Bi, and a two layer filter of Ti+Pb. To suggest the best moderator we have extracted nuclear data via the literature data.⁷⁾ We have examined the present model with taking one milligram of ^{252}Cf as embedded in the proposed neutron moderation system. Neutronic design studies for this system has been carried out using the MCNPX code. This code has been used to calculate the different components of the neutron and γ flux at the output window of the neutronic system with different filters.

Conclusion

The results show that Al_2O_3 is the best reflector, where produces a high epithermal neutron flux at the output window. Moreover, an assembly configuration of 30% AlF_3 +70% Al moderator/ Al_2O_3 reflector/ a two layer filter of Ti+Pb reduces the fast neutron flux at the output window much more than other assembly combinations (compare values in Table 1). In comparison with recent model suggested by Ghassoun et al.,⁶⁾ the proposed arrangement provides a higher epithermal flux with relatively low contamination of γ -rays (see Fig. 6).

**Fig. 6.** Epithermal neutron and γ -rays flux reported by Ghassoun et al.⁶⁾

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Conflicts of Interest

The authors have nothing to disclose.

Availability of Data and Materials

All relevant data are within the paper and its Supporting Information files.

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