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Feasibility study on the use of uranium in photoneutron target and BSA optimization for Linac based BNCT

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ABSTRACT

A hybrid photoneutron target including natural uranium has been studied for a 20 MeV linear electron accelerator (Linac) based Boron Neutron Capture Therapy (BNCT) facility. In this study the possibility of using uranium to increase the neutron intensity has been investigated by focusing on the time dependence behavior of the build-up and decay of the delayed gamma rays from fission fragments and activation products through photo-fission reactions in the BSA (Beam Shaping Assembly) configuration design. Delayed components of neutrons and photons were calculated. The obtained BSA parameters are in agreement with the IAEA recommendation and compared to the hybrid photoneutron target without U. The epithermal flux in the suggested design is 2.67E9 (n/cm^{2}s/mA).

1. Introduction

BNCT (Boron Neutron Capture Therapy) is a binary therapeutic modality currently considered for radioresistant tumors (such as melanoma) but also considered for extended ones (liver, stomach and lung) and for tumors located in or near vital organs (brain, such as the Glioblastoma Multiforme (GBM)) [1–5].

The BNCT treatment requires the selective loading of tumor tissue with a ^{10}B enriched compound and the subsequent irradiation of boron with low energy neutrons ($<$10 keV). The charged particles in the ^{10}B(n,α)^{7}Li reaction have tissue in range of less than 10 μm so that theoretically the tumor cells are destroyed selectively. The attenuation of thermal neutrons is so large that it is not easy to treat deep stated tumors. Irradiation by epithermal neutrons (1 eV$<$E$<$10 keV) is desirable to improve neutron penetration [6–7].

The facilities available for NCT clinical trials are limited. Suggested neutron sources for this purpose have included reactors, accelerator based neutron source and ^{252}Cf [8–12]. The IAEA recommended values for a neutron beam in BNCT are shown in Table 1 [6]. The two main limitations are the lack of specificity of the boron carriers (that is their disability to recognize the tumor cells) and the need of a thermal/epithermal flux of at least 5E8 n/cm^2/s with a reduced contribution from the fast part of the spectrum and from the residual gamma component. BNCT has no possibility of becoming a standard therapy if a hospital based neutron source would not become available so we used an electron accelerator to produce neutron. Photoneutrons are produced through (e,γ) and (γ,n) reactions in materials with a large (γ,n) cross section [13–14]. Disadvantage of using an electron accelerator is a low neutron flux, which can be improved using appropriate photoneutron materials.

We used a Linac with 20 MeV electrons. In our previous work, photoneutron materials in various dimensions and configurations were investigated and the most efficient target was introduced as the hybrid target that increased the neutron flux [15]. The BSA (Beam Shaping Assembly) design and the in-phantom depth dose distribution analysis of brain tumors for verification of a beam model were also presented for the hybrid target [16].

The investigation on photoneutron targets shows that uranium produces much more neutrons in comparison to other photoneutron targets [15,17]. In this study uranium was used in the hybrid target. The major problem in the application of U is the delayed gamma contaminations from fission fragments, which may be improved by shielding considerations.

2. Materials and methods

Tungsten was used as a photon target [14]. Monte Carlo calculations have been performed using the MCNPX code [18] to study the optimization of the photoneutron yield and various

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Table 1
IAEA recommended limits for fluxes and doses at the BSA exit for BNCT.

Neutron energy	$1\,eV \le E_n \le 10\,keV$
Intensity	$> 5 \times 10^8$ n/cm^{2}s
φ_{ep}/φ_t	> 20
$D^{\bullet}{}_{\gamma}/\phi_{ep}$	$< 2 \times 10^{-13}$ Gycm^2
$D^{\bullet}{}_{nf}/\phi_{ep}$	$< 2 \times 10^{-13}$ Gycm^2
J/φ	> 0.7
Beam size aperture (BSA exit window)	12–14 cm

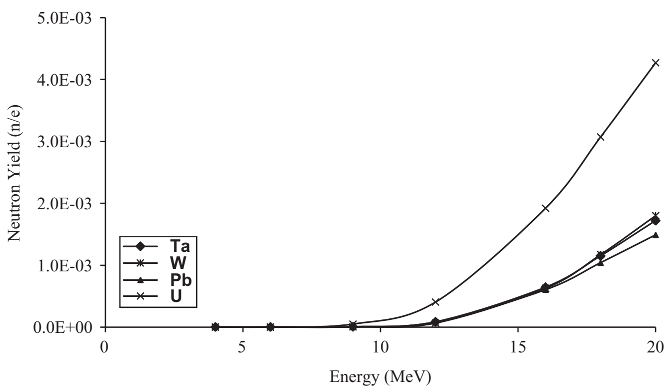

Fig. 1. Comparison of neutron yield of photoneutron targets: Ta, W, Pb and U.

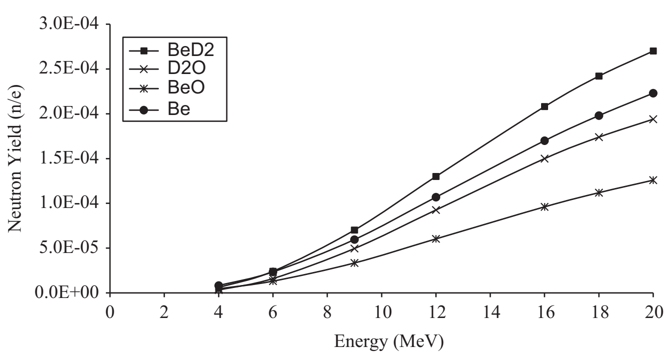

Fig. 2. Comparison of neutron yield of photoneutron targets: BeD_2, D_2O, BeO and Be.

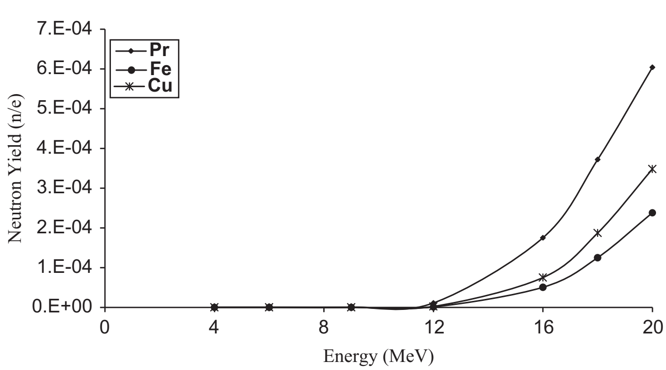

Fig. 3. Comparison of neutron yield of photoneutron targets: Pr, Fe and Cu.

photoneutron targets with different thicknesses and radii (but dimensions were the same in view point of neutron mean free path) containing Be, D, U, Pb, Ta, Fe, Pr and Cu in the cylindrical geometry. The neutron yields of these targets are shown in Figs. 1–3. As can be seen neutron flux is maximum using uranium

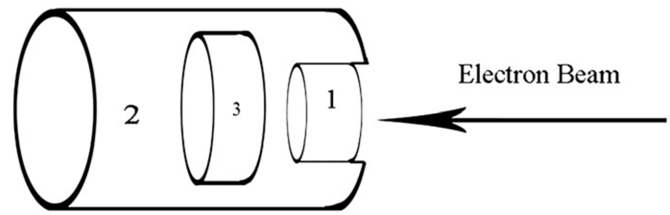

Fig. 4. Hybrid photoneutron target including BeD_2 and W, (1): electron/photon target, (2): BeD_2 photoneutron converter and (3): W Photoneutron converter.

as a target. Neutrons are generated in the uranium target from the following nuclear reactions: (γ,n), (γ,f), (γ,2n) and (γ,3n).

In [8], a hybrid target of BeD_2 (10 cm in radius and 12 cm in thickness) and W (8 cm in radius and 2 cm in thickness) (Fig. 4) resulted the best one in terms of neutron intensity. In this study, W has been substituted with uranium. The BeD_2 around the U moderates fast neutrons and due to a lower (γ,n) threshold produces more neutrons with low energy photons, which come from the U region. The neutron flux is increased using uranium in BNCT facilities but gamma contamination is also increased through build-up and decay of gamma rays from fission fragments, which exist even after Linac is switched off.

Therefore, the total gamma dose due to prompt gammas from the hybrid converter, the activation of materials and the delayed gamma rays should be calculated during the treatment time and it must be reduced to the recommended dose value [6].

The total neutron spectrum including prompt and delayed neutrons, and also gamma contaminations from prompt and delayed gamma rays during the treatment time has been calculated. It should be considered that a 20 MeV monochromatic electron beam was used in the simulations.

3. Results

3.1. Hybrid photoneutron source using U

Uranium was studied in different geometries in BeD_2. Neutron flux was calculated at the exit of the photoneutron converter using the MCNPX code. Table 2 shows the total neutron yield, which includes both the prompt and delayed neutrons. The features of the target with the maximum neutron yield are shown in Fig. 5.

The treatment time in BNCT is less than 1 h [6], so the delayed neutron and gamma fluxes were calculated at the exit of the hybrid target on this time basis.

Fig. 6 shows the prompt photoneutron spectrum of this hybrid target with U in comparison to the photoneutron spectrum of the hybrid target with W. Fig. 7 compares the photon contamination of these hybrid targets.

It can be seen that only the yield of the neutron production is improved in the hybrid target with U while the neutron spectrum shows no important changes. According to this point, we used the optimized BSA presented in the previous work to shape the neutron beam of the optimized hybrid target including U [15]. The BSA contains 10 cm Fe, 30 cm MgF_2 and 10 cm CF_2 in a cylindrical geometry and 10 cm of Ni was selected as a collimator material in the conical shape (45° in aperture).

As shown in Fig. 8, 25 cm of Pb, 5% borated polyethylene and 1 mm of Cd were also used as a reflector, neutron shield and thermal neutron filter, respectively.

Fig. 9 shows the shaped photoneutron at the BSA exit with the U hybrid target in comparison to the W one. It can be seen that neutron flux improves using uranium. Table 3 shows the