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Optimization of an accelerator-based epithermal neutron source for neutron capture therapy

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Abstract

A modeling investigation was performed to choose moderator material and size for creating optimal epithermal neutron beams for BNCT based on a proton accelerator and the $^7Li(p,n)^7Be$ reaction as a neutrons source. An optimal configuration is suggested for the beam shaping assembly made from polytetrafluoroethylene and magnesium fluorine to be placed on high current IPPE proton accelerator KG-2.5. Results of calculation were experimentally tested and are in good agreement with measurements.
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1. Introduction

Main problem in creating facilities for neutron capture therapy is to obtain neutron beams with energy spectrum and intensity acceptable for providing treatment. Nowadays at several nuclear reactors were created BNCT facilities (Binns et al., 2002; Harling and Riley, 2002; Harling et al., 2002; Moss et al., 1997) with complex engineering systems consisting of uranium converter, moderators, filters, collimators and shielding for epithermal neutron beams to produce necessary energy distribution and intensity. Nuclear reactors as neutron source for radiation therapy have such important feature as temporal and spatial stabilities of neutron flux, but constructing such facilities in oncology centers looks impossible. The problem arises from requirements of nuclear safety and high costs of building and maintaining such facilities. This problem has in the past decade prompted much active discussion and investigations of creating neutron sources for neutron capture therapy based on proton accelerators with beam energy 2–3 MeV and power 10–20 kW, which are more cost-effective and readily acceptable in oncology clinics (Allen and Beynon, 1995; Bayanov et al., 1998; Bluel et al., 1998; Wang et al., 1989). The most promising nuclear reaction for neutron generation on such an accelerator is $^7Li(p,n)^7Be$ (Kononov and Stavisski, 1976). Calculations show that with such a neutron source and a compact moderator it is possible to create neutron beams suitable for neutron capture therapy purposes. Such kind neutron source is now under construction on IPPE high current proton accelerator KG-2.5.

2. Materials and methods

Presented here are investigations in choosing optimal moderator material, optimization of the moderator size,

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and calculations and measurements of characteristics of epithermal neutron beam at the output port of moderator assembly. Spatial-energy distributions of neutrons from ^{7}Li(p,n)^{7}Be reaction from thick metallic lithium target are calculated by using methods and programs previously described (Kononov et al., 2003, 2003a). Main investigations were carried out for initial proton energies of 2.3, 2.4, and 2.8 MeV. Maximum neutron energies resulting in these interactions are 0.6–1.0 MeV and total calculated neutron yield 6.3×10^{12}, 8.1×10^{12} and 1.37×10^{13} neutron per second for beam current 10 mA. This data are in good agreement with direct total neutron yield measurements (Allen and Beynon, 1995).

Neutron and gamma-ray transports were calculated by using Monte Carlo computer codes S-95NCT and MCNP (Briesmeister, 1997; Zhitnik, 1993). The sphere moderator model was chosen for investigating characteristics of different materials for creating epithermal neutron sources based on ^{7}Li(p,n)^{7}Be reaction. In the center of the sphere was placed a source as a thin disk with a diameter of 4 cm, which is connected to the beam-line tube of the same diameter. Detectors were chosen as ring surfaces on the sphere taken with a step of $30°$ from beam axis with the angle $\pm 15°$. Calculations were done for spheres of radii form 16 to 28 cm.

Two parameter were used as criteria for choosing material and optimum moderator size: ϕ_{epi}—epithermal neutron leakage flux density (neutron energy more then 1 eV) from sphere surface for proton current of 10 mA, and $\dot{D}/\phi_{epi}$—neutron and gamma-ray dose rate in tissue per one epithermal neutron. The value of the latter was constrained to be less then $\sim 2.8 \times 10^{-12}$ RBE Gy cm^2 (Harling and Riley, 2002). In the calculation, biologically weighted absorbed-dose kerma and RBE factors presented in (Kononov et al., 2003a) were used. Different materials were tested, which consisted of elements with high elastic scattering cross section for fast neutrons and low absorption and activation cross sections in low-energy region, also their availabilities as chemical compounds were investigated.

Fig. 1 presents results obtained in investigations for readily available moderators—heavy water, magnesium fluorine, polytetrafluoroethylene (Teflon®) and Fluental®. Fluental® is used in some facilities for neutron capture therapy. It is clear from Fig. 1 that magnesium fluorine exhibits the best characteristics for creating epithermal neutron beams. It comes from the fact that magnesium and fluorine have strong resonance structure in elastic scattering cross section for fast neutrons; moreover, fluorine has high cross section of inelastic neutron scattering with low levels (110 and 197 keV) of excitation, and also these two elements have small atomic masses. Magnesium fluorine density is 3.14 g/cm^3. Optimal magnesium fluorine moderator thickness is 20 cm. Fig. 2 shows epithermal neutrons spectra from
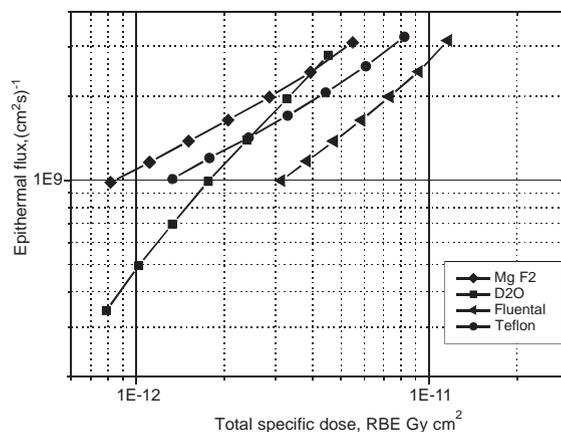
Fig. 1. The computed results obtained in investigations for readily available moderator materials: namely, heavy water, magnesium fluorine, polytetrafluoroethylene (Teflon®) and Fluental®.
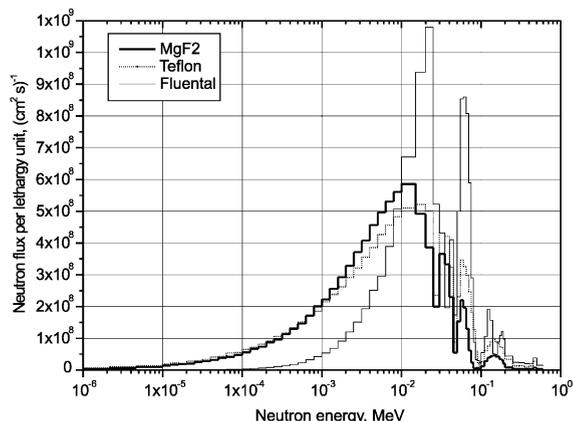
Fig. 2. Diagram shows epithermal neutrons spectra from the surface of a sphere moderator with a radius of 20 cm made from different materials.

the surface of a sphere moderator with a radius of 20 cm made from different materials. Neutron source is based on ^{7}Li(p,n)^{7}Be reaction in a thick metallic lithium target, placed at the center of the sphere (proton energy 2.3 MeV, beam current 10 mA). This figure clearly demonstrates that a moderator made of magnesium fluorine produces more appropriate neutron spectra for neutron capture therapy, with minimum amount fast neutrons and provide lowest radiation damages of surface tissue in comparison with others. Neutron activations of magnesium fluorine are small.

More detailed characteristic of epithermal neutron beam was derived in calculation of in-phantom absorbed-dose distribution. In this calculation, a cube beam-shaping assembly, with a size of $40 \times 40 \times 40$ cm^3,

was used. Accelerator target was placed at the center of the cube. For simulation, a cube ($20 \times 20 \times 20\,cm^3$) was used as a simplified head-like phantom model. The cube had three layers—from a front side to 0.5 cm and from 0.5 to 0.8 cm for simulation skin and scalp, and all other volume represented brain tissue. Detector structure and tissue composition was described in detail elsewhere (Kononov et al., 2003a, b).

3. Results

Fig. 3 shows various components of biologically weighted absorbed dose distribution through phantom
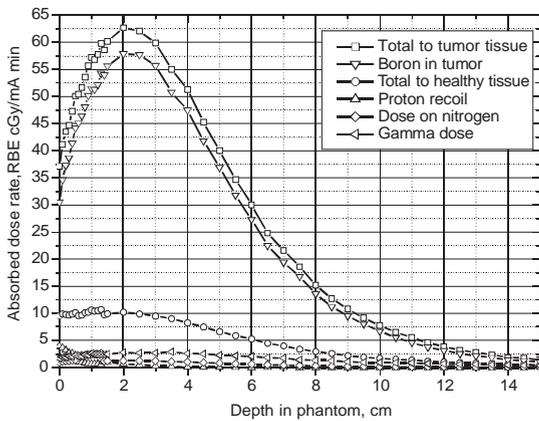
Fig. 3. Diagram shows various components of biologically weighted absorbed dose distribution through phantom depth in centerline.

depth in centerline, employing a moderator made from magnesium fluorine. In absorbed dose rate calculation, it was assumed that boron-10 concentration in healthy tissue was 18 ppm and in tumor 65 ppm, and RBEs for $^{10}B(n,\alpha)^7Li$ reaction are 1.3 and 3.8 in healthy tissue and tumor, respectively (Binns et al., 2002; Harling and Riley, 2002). For a beam shaping assembly made of polytetrafluoroethylene, absorbed dose distribution for tumor tissue is the same as presented in Fig. 3, but dose rate in healthy tissue (especially in skin) is 1.25 times higher than that with magnesium fluorine. For Fluental® moderator, a 1.5 times increase in dose rate is observed in healthy tissue, at the same time a 1.2 times decrease in dose in tumor at all phantom depths. Therefore, in terms of absorbed dose rates in tumor/healthy tissue, the beam shaping assembly made from magnesium fluorine is 1.25 times more effective than polytetrafluoroethylene, and 1.8 times more effective than Fluental®. Because polytetrafluoroethylene is cheaper than magnesium fluorine, calculations were performed for a combined beam shaping assembly made from polytetrafluoroethylene, with a block of magnesium fluorine placed on beam axis at downstream of the neutron production target Fig. 4. Calculation results show that the optimal block size is $20 \times 20 \times 20\,cm^3$ and dose distribution are the same as presented in Fig. 3.

BNCT beam quality is usually characterized by following parameters: advanced depth, advanced depth dose rate, therapeutic rate, and advantage rate. These parameters could be found by using data in Fig. 3. Table 1 shows the values of these parameters for epithermal neutron source based on an accelerator
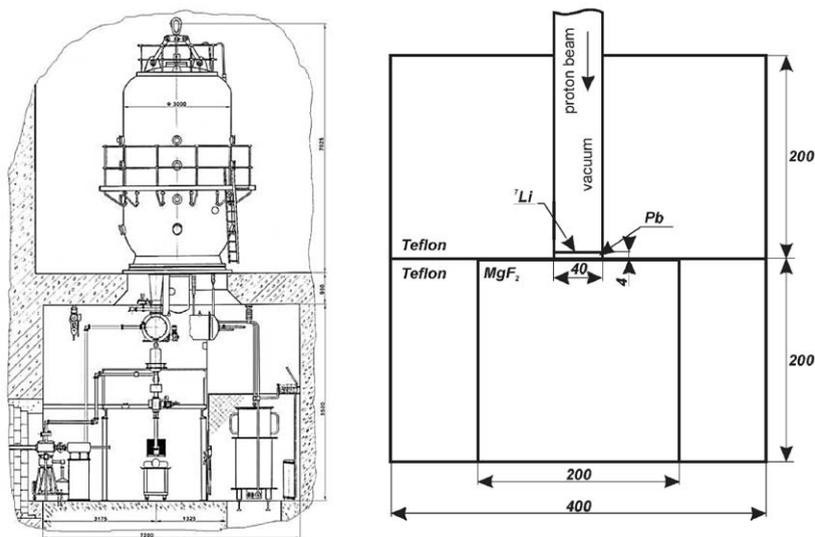
Fig. 4. Proposed BNCT facility on IPPE KG-2.5 accelerator and perspective beam shaping assembly. Phantom placed on a beam line center directly after MgF_2 block.

Table 1
Comparison of basic characteristics of accelerator-based facility with beam shaping assembly made from magnesium fluorine and polytetrafluoroethylene and the FCB MIT facility

	AD (cm)	TR_{max}	ADDR (RBE cGy/min)	AR	J_{epi}/ϕ_{epi}
Accelerator facility	9.1	6.2	100 (current 10 mA)	5.6	0.64
FCB MIT	9.3	6.4	125	6	0.84 and more

(proton current 10 mA), with $^7Li(p,n)^7Be$ neutron production target, and a combined beam shaping assembly block made from polytetrafluoroethylene and magnesium fluorine. They are compared with the values obtained for an epithermal neutron source based on a nuclear reactor (Binns et al., 2002). The comparison shows that the epithermal neutron beam quality and intensity from an accelerator are as good as those produced by a 5 MW nuclear reactor (Binns et al., 2002).

For direct verification of these calculations, further computer modeling was performed and thermal neutron flux was measured inside a water phantom. All experiments were done at the electrostatic Van-de-Graaf generator EG-2.5 of IPPE. Natural metallic lithium was used as a target. Beam shaping assembly with size $40 \times 40 \times 40$ was made from polytetrafluoroethylene. Lithium target was placed at its center. Water phantom had size $20 \times 20 \times 20 \, cm^3$. Proton beam charge was measured by a current integrator, thermal neutron beam flux measurement was performed by gold foil activation method, and resonance neutron contribution was evaluated by cadmium ratio method. To estimated absolute activity, gold foil measurements were performed using scintillation gamma-spectrometer with a NaI(Tl) crystal with cavity and previously measured efficiency.

To compare the results of computer modeling with experiment, doses were calculated based on measured thermal neutrons flux density, which was created in water by $^7Li(p,n)^7Be$ reaction. Same values of ^{10}B concentration, kerma-factors, and RBE as in computer modeling were used. Comparison of absorbed doses between calculation results and experimental measurements is presented in Fig. 5.

Basically, absorbed dose calculation consists of three stages: theoretical calculations of spatial-energy distribution and neutron yield from the accelerator target for $^7Li(p,n)^7Be$ reaction, Monte Carlo calculations of spatial-energy distribution of gamma rays and neutrons during transport in beam shaping assembly, and Monte Carlo calculation of in-phantom spatial distribution of thermal neutrons. The good agreements between calculation results and experimental measurements indicate that epithermal neutron source is modeled correctly in all three steps.
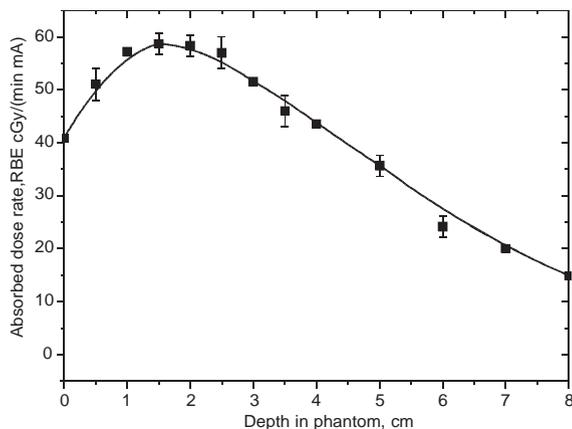
Fig. 5. Comparison of absorbed doses between calculation results (line) and experimental measurements (points) is shown.

4. Conclusion

A modeling investigation was performed to choose moderator material for creating optimal epithermal neutron beams for BNCT based on a proton accelerator and the $^7Li(p,n)^7Be$ reaction as a neutrons source. It has shown that the best characteristics are obtained using magnesium fluorine. An optimal configuration is suggested for the beam shaping assembly made from polytetrafluoroethylene and magnesium fluorine. Calculations of in-phantom dose distribution show that, with such a moderator and a 2.3-MeV and 10-mA proton beam, the advanced depth is 9 cm, therapeutic ratio is 6 at 3-cm depth, advanced depth dose rate at 9-cm depth is ~ 1 RBE Gy per minute, which means that maximum treatment time will be about 10 min.

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