PROCEEDINGS OF SCIENCE

Near-threshold ^{7}Li(p,n)^{7}Be reaction for Boron Neutron Capture Therapy

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Within the framework of accelerator based Boron Neutron Capture Therapy, a project to develop a folded Tandem-ElectroStatic-Quadrupole accelerator is under way at the Atomic Energy Commission of Argentina. The proposed accelerator is designed to deliver a 30 mA current of protons of up to 2.5 MeV. This work explores the production of neutrons by the ^{7}Li(p,n)^{7}Be reaction in a near threshold ($\gtrsim$ 1.88MeV) energy regime to obtain neutron beams to treat deep seated tumors. Results show that treatments of high quality can be obtained in this regime.

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1. Introduction

Boron Neutron Capture Therapy (BNCT) [1] is a binary radiation therapy under development for the treatment of certain types of tumors like melanoma and glioblastoma multiforme. BNCT consists in two steps. In the first step a ^{10}B-labeled drug with selective tumor cell targeting is administered to the patient. In the second step the patient is irradiated with a neutron beam. The neutron energy spectrum must satisfy that neutrons reach the tumor with thermal energy to take advantage of the large ^{10}B(n,α)^{7}Li neutron capture cross section (3840 b). Both residual fragments have energies of the order of 1 MeV and hence high linear energy transfer (LET) and range of the order of a cell diameter so that they have a lethal and very localized effect on tumor cells.

The BNCT success depends essentially on the concentration and specificity of the boron labeled drug and on the neutron beam quality. The present work centers its effort on the neutron beam generation.

Until now, all clinical trials have been carried by using nuclear reactors as neutron sources. However, there is a significant level of consensus internationally that advancement of BNCT requires neutron sources suitable for installation in hospital environments. Ion accelerators can fulfill this requirement and in principle can also provide better treatment qualities by choosing adequate nuclear reactions with softer primary neutron energies, which are closer to the ideal epithermal spectrum than those produced by nuclear reactors.

Deep tumors require an epithermal (i.e. between 0.5 eV and 10 keV) neutron beam, since neutrons lose energy as they penetrate the patient tissue. Neutrons within this energy range reach the tumor with thermal energies, for which the neutron capture in boron has the mentioned very high cross section. Neutron production reactions deliver neutrons with energies higher than needed and they thus need to be moderated before reaching the patient. Low energy neutron contamination in the beam produces dose to healthy tissue without reaching the tumor. High energy neutrons deliver dose to healthy tissue via elastic collisions with hydrogen. The goal is to obtain the most pure epithermal beam.

In our group, a dedicated Tandem Electrostatic Quadrupole accelerator devoted to Accelerator-Based BNCT (AB-BNCT) is under development and construction [2]. The accelerator should be capable of delivering 30 mA of protons and deuterons of energies up to 2.4 MeV. Several reactions have been studied, in particular ^{7}Li(p,n)^{7}Be. This is an endothermic reaction, so the energy of the neutrons can be as low as desired at the expense of yield. In previous work we have studied the regime of proton energies about that of the resonance (2.3 MeV) [3]. In this regime a Beam Shaping Assembly (BSA) is needed in order to moderate and direct the neutrons. Several configurations have been obtained with good treatment qualities.

In this work we explore the ^{7}Li(p,n)^{7}Be neutron production reaction but in a different regime: bombarding proton energies near the reaction threshold. In this regime, neutrons are produced with energies much nearer to the optimal one for the treatment and thus no BSA is required. A simple bolus material between the port and the patient is sufficient for the small amount of moderation. Less unnecessary radiation is produced and the low neutron yield is compensated with the lack of losses in the BSA.

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2. Materials and Methods

The evaluation of the treatment capabilities has been done by means of numerical simulations. A Snyder head phantom was considered and dose depth profiles from a single irradiation from the zenith have been calculated. The irradiation setup (Fig. 2) consists in a realistic metallic lithium target with its cooling system. Neutrons are moderated in a tissue equivalent A150 bolus loaded with 10 % in mass 95 % enriched ^{6}Li carbonate, the bolus thickness was varied from 0.25 cm to 7.25 cm. Bombarding angles from 1.925 MeV to 2.05 MeV were evaluated. Angles from 0 deg to 160 deg with respect to the beam direction have been analyzed. In the case of angles in the range of 0 to 90 degrees, neutrons have to cross the target and the cooling system in order to reach the patient; in the case of greater angles the neutrons that deliver dose to the patient are those that have been back scattered in the cooling system.

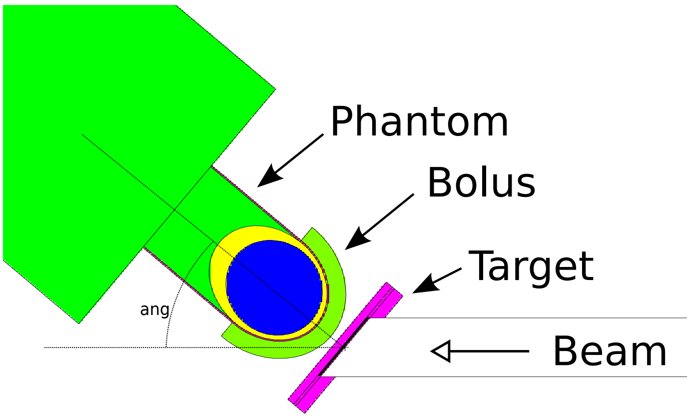

Figure 1: Neutron spectra as function of bombarding proton energy.

Neutron transport simulations have been made with MCNP5 [4]. Simulations start from the neutrons emitted in the reaction. The neutron yields and double differential spectra have been calculated following Lee [5] but with updated cross section data. All simulations consider a 30 mA beam, as this is the specification of the accelerator under construction in our group.

Depth dose profiles have been calculated for a single irradiation field. The treatment prescription was to maximize the irradiation time without exceeding the tolerances of healthy tissues; considered as 11 Gy-Eq for punctual dose in healthy brain, 16.7 Gy-Eq for healthy skin and 7 Gy-Eq for mean dose in whole brain [6]. The maximum irradiation time is limited to 60 min. Relative Biological Efectiveness (RBEs) factors were used for converting physical dose to equivalent dose for different types of irradiation. In the case of the dose due to captures in boron the equivalent dose also depends on the boron carrier, Compound Biological Effectiveness (CBE) is used in this case. These factors and the boron concentration in each tissue are the same as in our previous work [3]. The optimal configuration is the one that maximizes the tumor dose at any position, treatments must deliver tumor doses greater than 40 Gy-Eq to be considered satisfactory.

3. Results

Calculated neutron yields are shown in figure 2. Neutron yield increases with the bombarding energy but also the resulting neutron energies increase. Lower neutron energies are much simpler to moderate to the requirements of BNCT, but higher total yields are desirable, a good configuration will be a balance between them. Neutron spectra have a pronounced angular dependance, as an example figure 3 shows the case of bombarding energy of 1.925 MeV. This fact enforces that the optimization should analyze the correct patient angle.

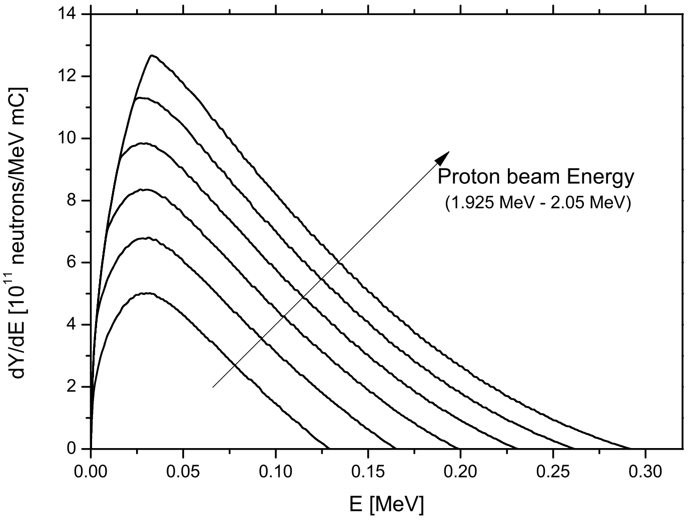

Figure 2: Neutron spectra as function of bombarding proton energy.

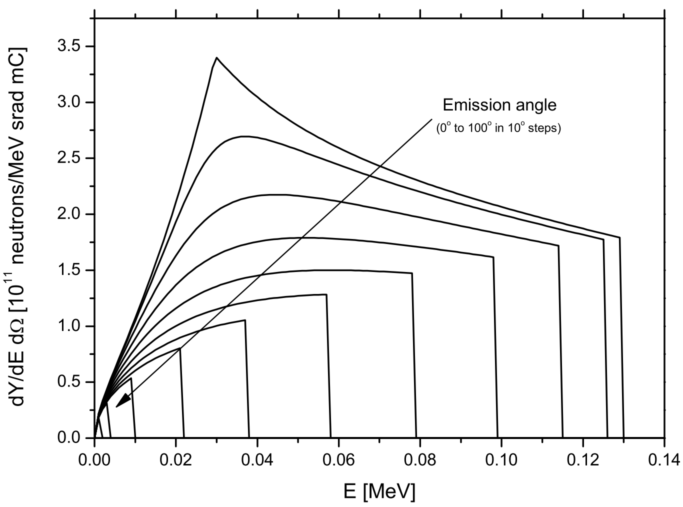

Figure 3: Double differential neutron yield of ^{7}Li(p,n)^{7}Be in the case of 1.925 MeV bombarding energy.

There exists a bolus thickness that maximizes the tumor dose for each bombarding energy and phantom's angle, this tumor dose is shown in figure 4. This figure shows that every bombarding energy has its optimal phantom angle. All of the bombarding energies analyzed offer good treatment capabilities. Figure 5 shows the depth dose profiles of the best obtained configuration which corresponds to 1.925 MeV bombarding irradiation, 60 deg phantom angle and 4.75 cm bolus thickness for a 55.5 min treatment time. Figure 6 shows the maximum tumor dose for each the analyzed configuration versus the irradiation time, many configurations can deliver enough tumor dose for a successful treatment in less than 60 min. It must be emphasized that irradiation time and beam current are inversely related and for instance with 2.025 MeV bombarding energy, 100 deg pahntom angle and 3.25 cm bolus thickness it is possible to obtain 40.9 Gy-Eq in 6.16 min with a 30 mA beam current which is equivalent to a 60 min irradiation time with a beam current as low as 3.08 mA.

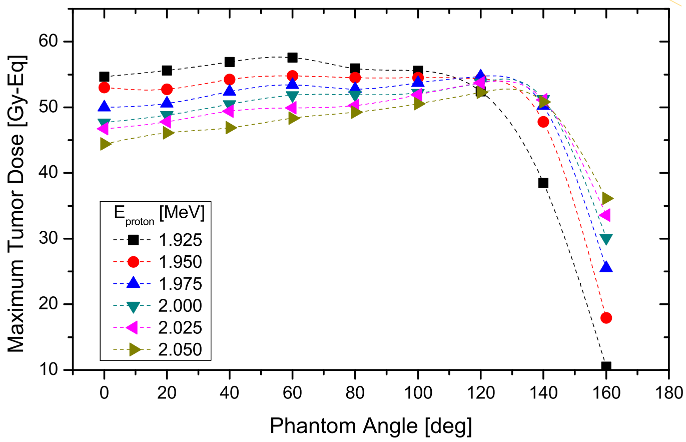

Figure 4: Best tumor dose that can be obtained for each bombarding energy and phantom angle combination.

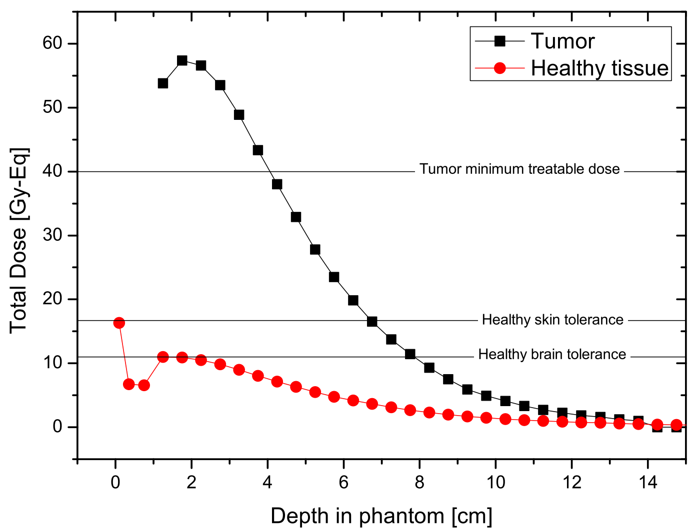

Figure 5: Tumor and healthy tissue depth dose profiles for the best case with 1.925 MeV protons.

4. Conclusions

Near threshold ^{7}Li(p,n)^{7}Be has been evaluated as a neutron source for BNCT. Several combinations of bombarding energy, irradiation angle and bolus thickness can succeed in treating deep seated tumors by delivering doses above 40 Gy-Eq. The best obtained configuration corresponds

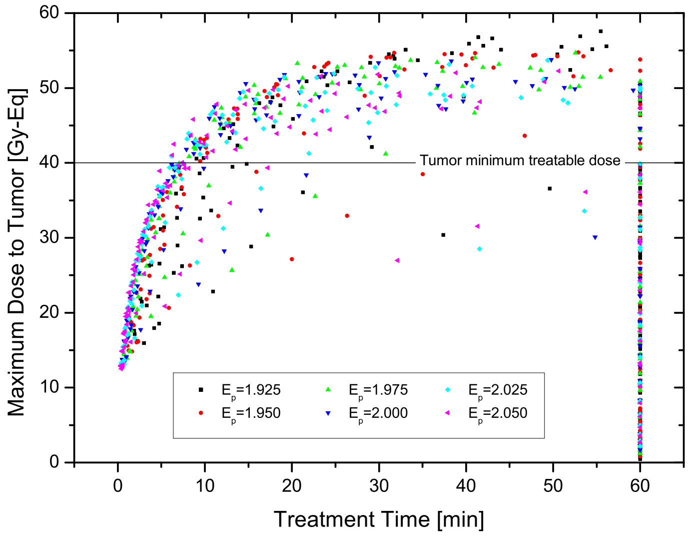

Figure 6: Maximum tumor dose for each of the analyzed configuration versus the irradiation time.

to 1.925 MeV bombarding irradiation, 60 deg phantom angle and 4.75 cm bolus thickness and delivers a maximum of 57.6 Gy-Eq dose to tumor in a a 55.5 min treatment time with a 30 mA beam current. It is possible to obtain enough doses to treat a tumor (considered here 40 Gy-Eq) with a beam current as low as 3.08 mA.

References

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