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ON OPTIMIZING THE ^{7}Li(p,n) PROTON BEAM ENERGY AND MODERATOR MATERIAL FOR BNCT

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ABSTRACT

The reaction ^{7}Li(p,n)^{7}Be has been proposed as an accelerator-based source of neutrons for Boron Neutron Capture Therapy (BNCT). This reaction has a large steep resonance for proton energies around 2.3 MeV which ends at approximately 2.5 MeV. It is generally accepted that the use of 2.5 MeV protons produces the highest yield of neutrons for BNCT. This paper suggests that for BNCT the optimum proton energy may be as low as 2.2-2.3 MeV. The evaluation of the clinical usefulness of the epithermal neutron beams investigated here has been based on depth-dose distributions in a head phantom.

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1. Introduction

Much work has been published [1-5] using the reaction ^{7}Li(p,n)^{7}Be for an accelerator-based BNCT facility. The majority of accelerator-based BNCT proposals to date involve 2.5 MeV protons incident on a metal ^{7}Li target. Neutrons are produced via the reaction ^{7}Li(p,n)^{7}Be. These neutrons must be slowed down in energy, via a filter (moderator/reflector) assembly, by roughly 2-4 orders of magnitude for BNCT treatments since the neutron distribution from the target peaks in the energy range of 400 to 700 keV in the forward direction for 2.5 MeV incident protons. A generally accepted [2] useful neutron energy range from the filter assembly for treating deep-seated tumors is 1 eV to 10 keV. In this paper we examine the optimum proton beam energy for different moderator and reflector combinations to produce the best neutron characteristics for BNCT.

2. Neutron source Characterization

The reaction ^{7}Li(p,n)^{7}Be displays a large resonance in the forward direction around 2.3 MeV which extends to about 2.5 MeV. A careful tradeoff must be investigated between neutron yield and average neutron energy from the target. The ^{7}Li(p,n) cross section data [6] show a proportionally large high-energy neutron tail with increasing proton energy. The quantitative tradeoff is not readily apparent and a careful examination is needed.

A fortran program was written to calculate neutron double differential (angle and energy) distributions from the target as a function of incident proton beam energy. Liskien [6] has derived center-of-mass best values for normalized Legendre coefficients for predicting cross sections for the ^{7}Li(p,n)^{7}Be reaction. For a given proton energy, the cross section as a function of center of mass angle can be determined in the center of mass system by:

$$\frac{d\sigma}{d\omega}(\phi) = \frac{d\sigma}{d\omega}(0^\circ)\sum_i A_i P_i(\phi) \tag{2.1}$$

where A_i are the coefficients of the Legendre polynomials determined by Liskien and $P_i(\phi)$ are the Legendre polynomials as a function of center of mass scattered angle. Neutron double differential yields for intermediate energy protons are determined by using log-log interpolation of the Legendre coefficients.

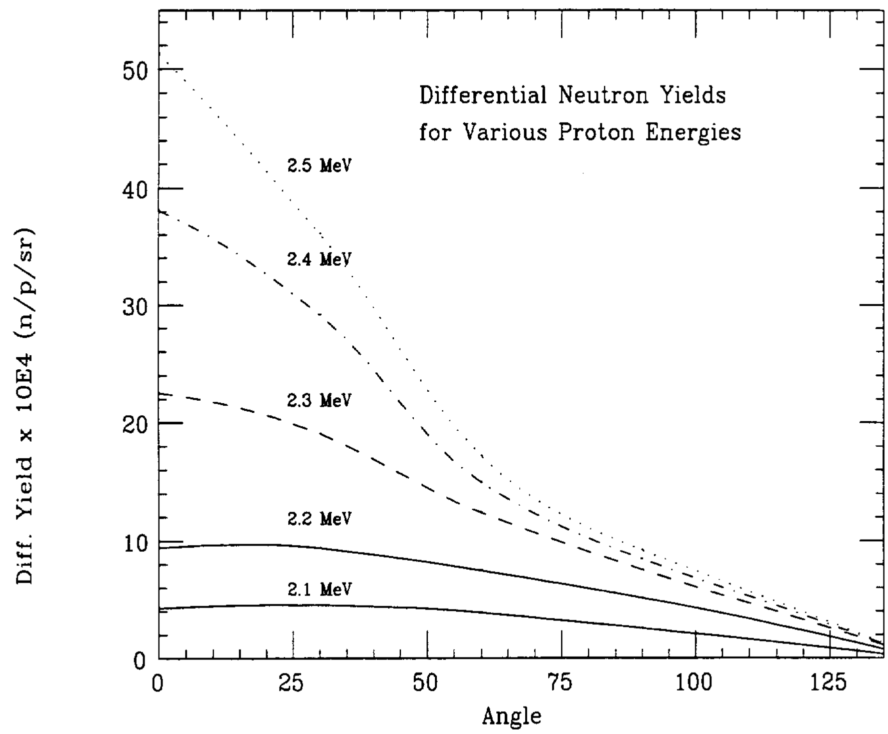

Figure 2.1: Differential neutron yields for protons on a thick ^{7}Li metal target.

The Q value for this reaction is given [6] as 1.644 MeV. The reaction thresholds are given by Liskien as 1.881 MeV in the forward direction and 1.920 MeV in the backward direction. In our program, the threshold which is used to determine the target thickness, is assumed to be 1.950 MeV. This is the lower energy limit of Liskien's Legendre fit to experimental data.

Only the reaction ^{7}Li(p,n)^{7}Be is considered. The reaction ^{7}Li(p,n)^{7}Be* which produces a 0.431 MeV gamma with a threshold of 2.373 MeV in the forward direction and 2.423 MeV in the backward direction, and the reaction ^{7}Li(p,n)^{7}Be** which produces a 4.55 MeV gamma with a threshold of 7.08 MeV are not considered in our treatment. These cross sections are only a few percent of the ^{7}Li(p,n)^{7}Be cross section at proton energies less than or equal to 2.5 MeV. In addition, the breakup reaction ^{7}Li(p,n^{3}He)^{4}He with a threshold at 3.692 MeV is not considered.

The target thickness is calculated by subtracting the range of the incident proton from the range of a proton at the threshold energy in Li metal. Using this method, only protons

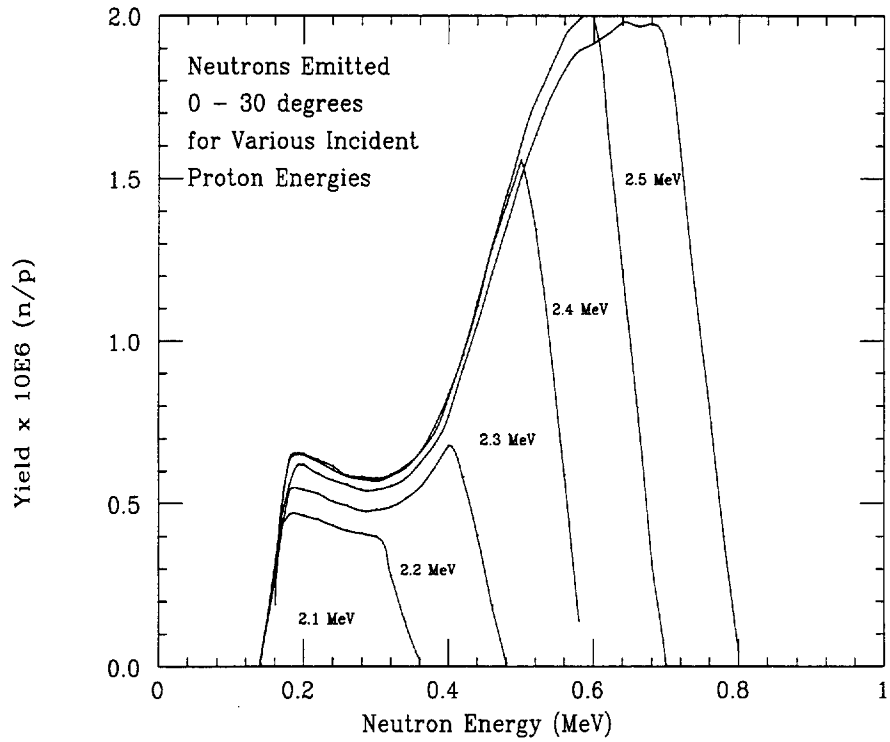

Figure 2.2: Neutron yields (per incident proton) as a function of neutron energy between 0° and 30° from various incident proton kinetic energies for the ^{7}Li(p,n)^{7}Be reaction.

with energies at or above the reaction threshold are allowed to deposit any energy directly in the target to minimize heating of the target. Range and stopping power data are taken from Janni [7] with log-log interpolation for intermediate energy values. The target is modeled as a large number of equal thickness layers. The proton energy is degraded in each layer and the neutron double-differential yield is calculated for each of these proton energies and then summed over the total target thickness. A more detailed description of this source program and filter geometry can be found elsewhere [8].

The neutron energy spectra for various angle bins and for various incident proton kinetic energies are shown in Fig. 2.2. This figure shows only those neutrons produced in the forward 30° cone with respect to the proton beam. The output from this program, for all neutron energies and angles, is used as the starting point for subsequent simulations of neutron transport in various moderator and reflector materials using MCNP [9].

3. Moderator/Reflector

Three moderator materials are considered: BeO, D_2O and Al/AlF_3 in a ratio of 40% Al and 60% AlF_3 [10]. We have not yet tried to optimize this ratio for our purposes. All designs assume an Al_2O_3 reflector.

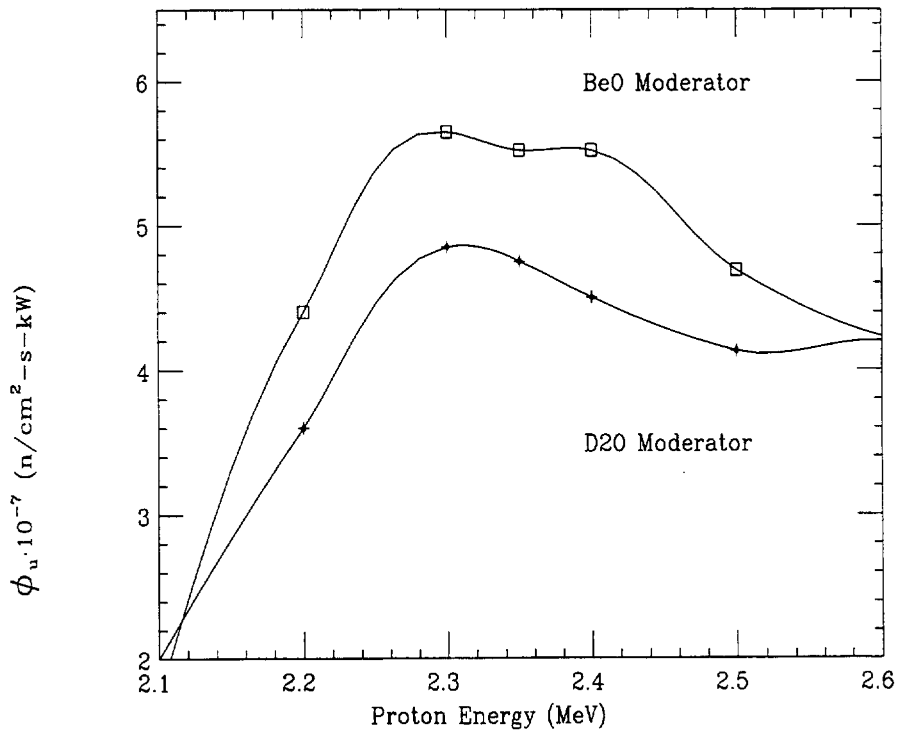

Figure 3.1: Useful neutron flux (Φ_u) versus proton energy. Each proton energy requires a different moderator thickness in order that the ratio of useful flux and total equivalent dose at the exit port be kept constant.

Fig. 3.1 is a plot of the useful neutron flux, Φ_u, as a function of the incident proton energy for the BeO and the D_2O moderators. Here, Φ_u is defined as the neutron flux at the irradiation point outside the moderator with energies between 1 eV and 10 keV. Each proton energy requires a different moderator thickness in order to keep constant the ratio of useful flux to the total equivalent dose at the exit port. This figure indicates that the peak in Φ_u occurs at approximately a proton energy of 2.3 MeV. This is roughly 20% higher Φ_u than one would obtain using a proton energy of 2.5 MeV. For the D_2O moderator there is less difference in Φ_u for proton energies between 2.3 and 2.6 MeV. The major problem with these results lies in the definition of Φ_u. The energy boundaries are subject to debate and all neutrons within these boundaries are given equal weight.

4. Clinical Efficacy Comparisons

Determining the effectiveness of one moderator design over another can be difficult and questionable when the useful flux outside the moderator is used as a figure of merit. A more direct method to determine the effectiveness of a design is to compare depth-dose profiles in the head. For this reason, the INEL BNCT_rtpe [11](radiation treatment planning environment) was used. This software is currently in use for the BNL/BMRR clinical trials. A routine was provided by INEL personnel which converts an MCNP surface source output file (SSW option) into a file containing the neutron and gamma current in equal probability angle bins as required by rtpe. MCNP output source files for each moderator and for several incident proton energies were converted and input to rtpe. CT scans were obtained from INEL personnel of a typical human head. The INEL program rtt (Monte Carlo simulation part of rtpe) geometry was based on these CT scans. The standard methodology is to run rtt with uniform 1 ppm ^{10}B in brain and tumor and to later multiply the ^{10}B dose by the measured ^{10}B concentration. Results are summarized in Table 1. Each case represents a different moderator thickness to approach the optimum for that proton energy.

The results for the proton accelerator using the $^7Li(p,n)$ reaction with a BeO moderator and for the Brookhaven Medical Research Reactor (BMRR) Al_2O_3 design indicate that their clinical efficacy is similar. Treatment time, maximum tumor dose and tumor dose at a depth of 8 cm are almost identical. The fast neutron dose is about a factor of two lower for the BeO moderator. This is due to the high-energy tail of the reactor fission spectrum which extends up to about 10 MeV. The accelerator with an Al/AlF_3 moderator shows a clear advantage for treating deep-seated tumors. The Al/AlF_3 results for 2.3 MeV protons or 2.5 Mev protons are similar. Both show an 8 cm tumor dose increase of about 35% over BMRR and the accelerator-based BeO design.

Table 4.1: Results with INEL treatment planning code, BNCT_rtt. The comparison includes the maximum thermal neutron flux in the tumor (Φ_{th}), the $^{10}B(n,\alpha)$ dose ($\dot{D}_B$), the fast neutron dose ($\dot{D}_F$), the gamma dose ($\dot{D}_\gamma$) and the $N(n,\gamma)$ nitrogen dose ($\dot{D}_N$). Treatment plan is based on BMRR plan with BPA - tissue: 13 ppm ^{10}B, tumor: 45.5 ppm ^{10}B, compound factor (includes RBE): 1.3 in tissue and 3.8 in tumor, RBE: 3.2 for D_F and D_N. The BMRR is assumed to be operating at 3 MW and the accelerator is assumed to be operating at 20 mA.

	BMRR	BeO		D_2O		Al/AlF_3	
	Al_2O_3	2.5 MeV (20 cm)	2.3 MeV (16 cm)	2.5 MeV (25 cm)	2.3 MeV (21 cm)	2.5 MeV (35 cm)	2.3 MeV (30 cm)
Φ_{th} (10^9 n/cm^2/s)	1.8	1.77	1.95	1.82	1.77	1.89	1.57
$\dot{D}_B$ (tissue, cGy/min)	13.3	13.1	14.6	13.6	13.2	14.2	11.7
$\dot{D}_F$ (tissue, cGy/min)	4.25	2.60	2.24	3.71	3.28	1.93	1.60
$\dot{D}_\gamma$ (tissue, cGy/min)	9.38	8.76	9.69	10.0	9.63	10.9	9.10
$\dot{D}_N$ (tissue, cGy/min)	4.25	4.20	4.66	4.34	4.23	4.53	3.80
Time (12.5 cGy) min	40.1	43.6	40.1	39.5	41.2	39.7	47.8
D_T (max,tumor) Gy	61.6	65.3	66.4	62.0	62.7	64.4	64.2
D_T (8 cm,tumor) Gy	18.5	19.6	19.9	17.4	18.8	25.8	25.7

The explanation for the increase in deep dose for the Al/AlF_3 can be seen by examining the neutron spectra at the exit to the the various moderators modelled in Fig. 4.1. The Al/AlF_3 clearly shows the hardest spectrum with an average neutron energy of about 10-20 keV. In contrast, the BeO, D_2O and the BMRR spectra have much lower average energies of about 10-100 eV. Spectra from 2.3 MeV proton beams are very similar. All cases, including BMRR, have a J/Φ ratio of about 0.6 at the exit of the moderator. These plots also show the inherent problem in choosing the upper boundary of the earlier-defined useful flux of 10 keV. The Φ_u for all spectra shown is within about 20% of each other yet the spectra peak at neutron energies more than two orders of magnitude apart but roughly within the boundaries of what is defined as useful.

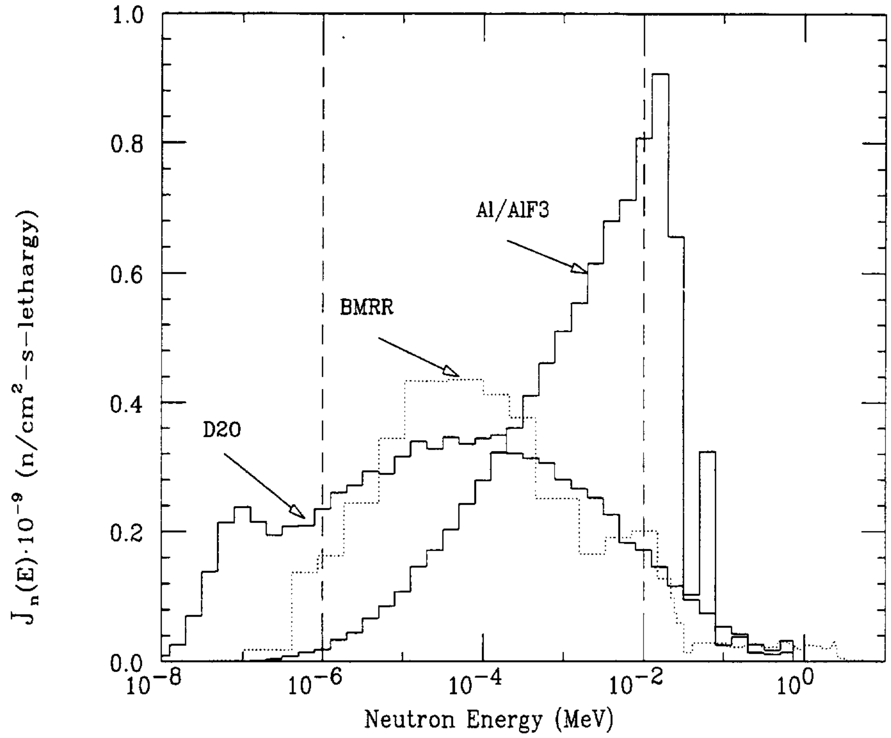

Figure 4.1: Neutron current spectra at the moderator exit port for various moderators: BMRR using Al_2O_3 (dotted line), and 2.5 MeV protons (solid lines) with BeO (peak about 10^{-4} MeV) and an Al/AlF_3 (peak about 10^{-2} MeV) moderator. The J/Φ ratio is approximately 0.6 for all cases.

5. Conclusions

For all moderator materials investigated there is very little difference in clinical efficacy for protons between 2.3 and 2.5 MeV. The performance of the Al/AlF_3 moderator is superior to that of D_2O and BeO for treating deep-seated tumors. It provides an 8 cm tumor dose approximately 30% higher for roughly the same treatment time and peak tumor dose. We have only investigated the composition of Al/AlF_3 in the ratio of 40% Al to 60% AlF_3 by weight. The current definition of useful flux provides only a very rough indicator of moderator performance and can even be misleading. It is recommended that if one is comparing the useful fluxes of various moderators at the moderator exit port that the upper boundary be extended to about 40 keV as proposed by Yanch [12]. Additionally, greater weight should be given to the higher energies for deep-seated tumor treatments.

6. Acknowledgements

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