Analysis of Accelerator Based Neutron Spectra for BNCT Using Proton Recoil Spectroscopy

L. Wielopolski¹, H. Ludewig², J.R. Powell², D. Raparia³, J.G. Alessi³ and D.I. Lowenstein³

¹Department of Applied Science, ²Department of Advanced Technology, ³Alternating Gradient Synchrotron, Brookhaven National Laboratory, Bldg. 490-D, Upton, NY 11973, USA

Introduction

Boron Neutron Capture Therapy (BNCT) is a promising binary treatment modality for high-grade primary brain tumors (glioblastoma multiforme, GM) and other cancers¹⁻³. BNCT employs a boron-10 containing compound that preferentially accumulates in the cancer cells in the brain. Upon neutron capture by ¹⁰B energetic alpha particles and triton released at the absorption site kill the cancer cell. In order to gain penetration depth in the brain Fairchild^{4,5} proposed, for this purpose, the use of energetic epithermal neutrons at about 10 keV. Phase I/II clinical trials of BNCT for GM are underway at the Brookhaven Medical Research Reactor⁶ (BMRR) and at the MIT Reactor, using these nuclear reactors as the source for epithermal neutrons.

In light of the limitations of new reactor installations, e.g. cost, safety and licencing, and limited capability for modulating the reactor based neutron beam energy spectra, alternative neutron sources are being contemplated for wider implementation of this modality in a hospital environment. For example, accelerator based neutron sources offer the possibility of tailoring the neutron beams, in terms of improved depth-dose distributions, to the individual and offer, with relative ease, the capability of modifying the neutron beam energy and port size.

In previous work new concepts for compact accelerator/target configuration were published^{7,8}. In this work, using the Van de Graaff accelerator we have explored different materials for filtering and reflecting neutron beams produced by irradiating a thick Li target with 1.8 to 2.5 MeV proton beams. However, since the yield and the maximum neutron energy emerging from the Li-7(p,n)Be-7 reaction increase with increase in the proton beam energy, there is a need for optimization of the proton energy versus filter and shielding requirements to obtain the desired epithermal neutron beam. The MCNP-4A computer code was used for the initial design studies that were verified with benchmark experiments using a proton recoil spectroscopy detection system. Comparison was also made between in phantom ¹⁰BF₃ readings made at the BMRR and those made at the RARAF accelerator facility.

Experimental Set-Up and Analysis

The experiments were carried out on a Van de Graaff accelerator at the Radiological Research Accelerator Facility (RARAF) at Nevis Laboratory, Columbia University. Measurements were made using a cylindrical 3 atm gas proportional proton recoil (PR) counter and a ¹⁰BF₃ counter. The PR counter was filled with partial pressures of 95.23% H₂, 4.76% CH₄ and 0.01% ³He for internal energy calibration purposes. Neutron spectroscopy was performed in air with the PR counter axis parallel to the central beam axis and in contact with the beam port. A small ¹⁰BF₃ counter was used in a phantom in the RARAF and the BMRR facilities for independent confirmation purposes.

The geometrical configuration of the target, filter and reflector assembly is shown in Fig. 1. This configuration was used for the Monte Carlo calculations and the experiments. In an alternative configuration the Be reflector was replaced with two Teflon and Fe disks, and in the third configuration both Mo and Be reflectors were replaced with two larger Teflon and Fe disks. In addition there was about 1 mm thick water layer for target cooling purposes. The model calculates

the neutron energy spectrum at the beam port and is used to estimate the current required to deliver an epithermal neutron flux of 10^{12} n/cm²/h required to treat a patient during one hour. The calculations were performed at several proton energies, although the main effort was directed to proton energies of 2.5 MeV. The MCNP code was run for 5 million histories and the results were normalized per one source neutron. To derive the beam current, a thick Li target neutron yield of 1.4×10^4 neutrons per proton at 2.5 MeV was used.

Figure 1. Schematic configuration of the filter assembly with the target. All the dimensions are in cm.

The measured pulse height distributions (PHD) were analyzed using the PSNS code⁹. The code is based on the characteristic of the n-p scattering kernel in which neutron energy transfer to proton is from zero to maximum neutron energy. This enables one to relate the measured PHD $M(E)$ to the neutron spectrum $\phi(E)$ through the following equations¹⁰, Eq. 1

$$M(E) = N_H T \int_E^{E_{\max}} dE_n \frac{\sigma(E_n)}{E_n} \phi(E_n)$$

where: E is the neutron energy, N_H is the number of hydrogen atoms in the active volume of the counter, T is the counting time in seconds and $\sigma(E)$ is the scattering cross section. Thus the neutron spectrum is unfolded by differentiating the measured PHD, Eq. 2, instead of the alternative unfolding scheme that involves matrix inversion.

$$\phi(E) = -\frac{E}{N_H T \sigma(E)} \frac{dM(E)}{dE}$$

Results

PHD measured for bare, without moderator, thin and thick Li targets using the PR counter and proton energy of 2.3 MeV, are shown in Fig.2. The neutron spectra resulting from unfolding of the PHDs shown in Fig. 2 are shown in Fig. 3.

Figure 2. Pulse height distributions measured from a bare thin and thick Li targets irradiated with 2.3 MeV proton beam.

Figure 3. Unfolded neutron spectra obtained from PHDs shown in Fig. 2.

The unfolded neutron spectra for the three filter/reflector configurations mentioned before and a bare target without filtration are shown in Fig. 4 for 2.5 MeV proton beam. The agreement between the measured spectrum of the Teflon iron filter configuration and the calculated one can be seen in Fig. 5. These two spectra were normalized to the same area in the energy interval between 35 and 200 keV. In this energy range there is minimal distortion due to background gamma radiation, that results

in low energy PHD in the measured spectrum, and there are no wall effects that potentially may occur due to high energy neutrons, at the high end of the spectrum. The maximum neutron energy due to 2.5 MeV protons is about 787 keV.

Figure 4. Unfolded neutron spectra for different filter/reflector configurations together with a neutron spectrum from a bare source. Proton energy is 2.5 MeV

Figure 5. Comparison between measured and calculated spectra at a proton energy of 2.5 MeV.

The epithermal neutron fluxes measured from the unfolded neutron spectra in the energy interval between 5, at present the lower energy limit of the PHD, and 35 keV were normalized per mC of proton charge. From these values estimates of the currents required to deliver a neutron fluence of 10^{12} n/cm² during one hour of treatment were obtained. These estimates were corrected, using ratios obtained from the MCNP calculations, to include epithermal neutrons from 1 eV up to 5 keV to be included in the current predictions. For the filter/reflector configurations considered here the mean correction factor is about 2.5. This correction factor should not be confused with the agreement between these predicted values, based on experiments, and the estimated currents based on the MCNP calculations as they are summarized in Table 1. The agreement is in the range of 20% to 70% and these results are similar to the lower values reported in the literature¹¹.

Table 1. The estimated proton beam currents required to deliver a fluence of 10^{12} n/cm² during one hour based on the measurements and calculations of the epithermal fluxes between 1 eV and 35 keV.

In order to obtain a partial independent confirmation of the predicted currents, a small ¹⁰BF₃ counter was used for measurements in phantom at the depth of maximum thermal flux. These measurements were taken in the epithermal port of the BMRR, where clinical trial are being carried at present, and at the RARAF accelerator facility. The phantom consisted of a 14x14x14 cm³ polyethylene cube with holes to accommodate the ¹⁰BF₃ counter at various location, and proper plugs for filling the unused holes. Based on the counts obtained from the ¹⁰BF₃ counter the estimated proton beam current required to deliver the same count rate as at BMRR at 3 MW, at a typical operating power during patient treatment, was about 1 mA for 2.5 MeV proton beam and about 6 mA for the 1.9 MeV proton beam. Earlier results using a small ¹⁰BF₃ counter in the BMRR facility were presented¹². In addition, lateral scans in air and in phantom, at the RARAF facility showed that the neutron beam resulting from 2.5 MeV protons is wider and flatter than that from 1.9 MeV protons.

Summary and Conclusions

Confirmation of the model used in the Monte Carlo calculations is vital in developing and characterizing therapy facility designs and treatment planning systems. The neutron energy spectra are of particular importance in accelerator-based BNCT when investigating the use of lithium or other elements as possible target material. The neutron spectra are needed: 1) as a source input file for transport calculations to develop suitable moderator and filter assemblies, 2) for evaluating accelerator beam current requirements and the target cooling schemes, 3) for evaluating facility shielding requirements, and 4) for proper in phantom dose calculations. The presented results show a good agreement between the measured and the calculated spectra. At present the low energy edge,

that have measured using the PR detector, is about 5 keV. However, neutron spectroscopy using PR detectors can be extended to about 1 keV. Based on these preliminary measurements, a proton beam of 5 mA appears to be adequate for use in BNCT. Such a beam will deliver an epithermal flux of 10^{12} n/cm² during a one hour irradiation, with a large beam port of about 10 cm in diameter.

Acknowledgements

The authors would like to thank Dr. Gerhard Randerf-Pehrson and Stephen Marino from the Radiological Research Accelerator Facility at Columbia University for their assistance in carrying out the experiments, and David E. Alburger for his measurements at the BMRR. This project has been funded by the Laboratory Directed Research and Development funds under the auspices of the U.S. Department of Energy Contract No. DE-AC02-98CH10886 .

References

1. P.A. Zahl and F.S. Cooper, Physical and biological considerations in the use of slow neutrons for cancer therapy. *Radiology* 37, 673-682, 1941.
2. W.H. Sweet, The uses of nuclear disintegration in the diagnosis and treatment of brain tumors. *New England Journal of Medicine*, 245, 875-878, 1951.
3. D.N. Slatkin, A history of boron neutron capture therapy of brain tumors. *Brain*, 114, 1609-1629, 1991.
4. R.G. Fairchild, Development and dosimetry of an epithermal neutron beam for possible use in neutron capture therapy. *Phys. Med. Biol.*, 10, 491, 1965.
5. R.G. Fairchild, J. Kalef-Ezra, S.K. Saraf, S. Fiarman, E. Ramsey, L. Wielopolski, B.H. Laster and F.J. Wheeler, Installation and testing of an optimized epithermal neutron beam at the Brookhaven Medical Research Reactor (BMRR), in: "Neutron Beam Design, Development and Performance for Neutron Capture Therapy," ed; O. Harling. and R. Zamenhof, Plenum Press, New York 1989, pp. 185-199.
6. J.A. Coderre, E.H. Elowitz, M. Chadha, R. Bergland, J. Capala, D.D. Joel, H.B. Liu, D.N. Slatkin and A.D. Chanana, Boron neutron capture therapy for glioblastoma multiforme using *p*-boronophenylalanine and epithermal neutrons: Trial design and early clinical results. *J. Neuro-Oncology* 33, 141-152, 1997.
7. J.R. Powell, H. Ludewig, M. Todosow and M. Reich, Proceedings of the ASME-JSME 4th International Conference on Nuclear Engineering -ICONE-4, pp. 493-502, 1996.
8. J.R. Powell, H. Ludewig, M. Todosow and M. Reich, Applications of Accelerators in Research and Industry, pp. 1309-1312, AIP Press, New York, 1997.
9. E.F. Bennett and T.J. Yule, *ANL-7763*, 1971.
10. N. Tsoulfanidis, "Measurements and Detection of Radiation," ch. 14, Hemisphere Publishing Corporation Washington, New York, London, 1983.
11. R.J. Kudchadker, J.F. Kunze and J.F. Harmon, "Advances in Neutron Capture Therapy," pp. 516-521, Elsevier, Amsterdam-Lausanne-New York-Oxford, 1997.
12. D.E. Alburger, D. Raparia and M.S. Zucker, *Med. Phys.*, 25, 1735-1738, 1998.

Table 1. The estimated proton beam currents required to deliver a fluence of 10^{12} n/cm² during one hour based on the measurements and calculations of the epithermal fluxes between 1eV and 35 keV.

Filter	Current Inferred from Measurements (mA)	Current Inferred from MCNP Calculations (mA)
No Filter	12.60	-----
Teflon, Fe No Reflector	8.96	-----
Teflon, Fe	2.22	1.28
Mo, Teflon, Fe	2.20	1.32
Mo, Be	1.62	1.33