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Near-threshold $^7\text{Li}(p,n)^7\text{Be}$ neutrons on the practical conditions using thick Li-target and Gaussian proton energies for BNCT

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HIGHLIGHTS

- Proton energy from 1.85 to 1.95 MeV were studied for near threshold $^7\text{Li}(p,n)^7\text{Be}$ neutrons.
- Practical conditions were applied for RFQ type accelerator and a thick Li-target.
- Gaussian distribution of proton energies were checked for the standard deviation of 0, 10, 20 and 40 keV.
- The mean energy of 1.92 MeV protons with Gaussian distribution of 20 keV was feasible.
- The suitable thicknesses of Lead layer as gamma absorber was about 3 cm.
- The suitable thicknesses of polyethylene BDE was about 24 mm at the proton current of 13 mA.

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ABSTRACT

The near threshold $^7\text{Li}(p,n)^7\text{Be}$ neutrons generated by incident proton energy having Gaussian distribution with mean energies from 1.85 to 1.95 MeV, were studied as a practical neutron source for BNCT wherein an RFQ accelerator and a thick Li-target are used. Gaussian energy distributions with the standard deviation of 0, 10, 20 and 40 keV for mean proton energies from 1.85 to 1.95 MeV were surveyed in 0.01 MeV increments. A thick liquid Li-target whose dimensions were established in our previous experiments (i.e., 1 mm-thick with 50 mm width and 50 mm length) was considered in this study. The suitable incident proton energy and physical dimensions of Pb layer which serves as a gamma absorber and a Polyethylene layer which is used as a BDE were surveyed by means of the concepts of TPD. Dose distribution were calculated by using MCNP5. A proton beam with mean energy of 1.92 MeV and a Gaussian energy distribution with a standard deviation of 20 keV at a current of 10 mA was selected from the viewpoint of irradiation time and practically achievable proton current. The suitable thicknesses of Pb gamma absorber was estimated to be about 3 cm. The estimated thickness of the polyethylene BDE was about 24 mm for an ideal proton current of 13 mA, and was 18 mm for a practical proton current of 10 mA.

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1. Introduction

Neutron irradiation systems (NIS) for boron neutron capture therapy (BNCT) using accelerators are now under development (Blue and Yanch, 2003). They can be categorized into two types: the first is the moderated neutron usage (MNU) which includes a beam shaping assembly (BSA) to slow down neutrons, while the other is the direct neutron usage (DNU). At present, the MNU can be realized using the $^9\text{Be}(p,xn)$ reaction with 30 MeV protons at 1 mA generated by a cyclotron (Tanaka et al., 2009). Other MNU using $^7\text{Li}(p,n)^7\text{Be}$ with 2.5 MeV protons at 20 mA generated by a radio frequency quadrupole (RFQ) are also being investigated.

The DNU, which has many advantages for hospital-based implementation due to its simpler and compact design, would be practical only with the near threshold $^7\text{Li}(p,n)^7\text{Be}$ reaction. In our previous study, the ideal conditions of a thin lithium target (Li-target) and mono-energetic protons for the near threshold $^7\text{Li}(p,n)^7\text{Be}$ reaction for BNCT were investigated using the concept of the treatable protocol depth (TPD) combined with the use of a boron dose enhancer (BDE) (Bengua et al., 2006, 2004; Tanaka et al.,...
The practical specifications of the Li-target thickness and proton energy and its fluctuation were studied in our earlier works (Kobayashi et al., 2008, 2007). An important consideration for a reliable BNCT irradiation system are the life-time of the target and the ease and safety in its handling. It has been shown in a related publication (Takahashi et al., 2011) that a liquid-lithium film jet-flow with a flow speed of about 30 m/s at 1 mm thickness and 50 mm width and 50 mm length would be a practical condition for a thick Li-target when a 3 cm diameter proton beam is used to generate neutrons for BNCT. In this paper, accelerator-based (acc-based) BNCT system employing the DNU system is investigated by considering an RFQ proton accelerator and a liquid Li-target. Parameters such as the effective thickness and shape of structural components of the system (e.g., stainless steel, insulator, lead (Pb) gamma-ray shielding) were considered in the optimization.

2. Materials and methods

2.1. Lithium target assembly design and simulation parameters

Shown in Fig. 1 is the target assembly design used in our simulations. Its components include a 1 mm thick Li-target, stainless steel, two kinds of insulators (i.e. SiO2 and SiO2−ZrO2) and a Pb gamma-ray shielding. A water phantom representing a human head is likewise shown.

Incident protons with Gaussian energy distributions were considered in this study. The production of neutrons and gamma rays were assumed to occur within the Li-target with a thickness of 1 mm.

The energy and angular distributions of neutrons from the 7Li(p,n)7Be reaction were obtained from the method described by Lee and Zhou (1999). This was applied for incident proton with mean energies from 1.881 to 2.100 MeV at increments of 0.001 MeV and assuming a Gaussian energy distribution. Finally, the neutron and gamma rays produced in the Li-target were estimated. Gamma ray yields from the Li-target were computed based on the formula derived from empirical data (Lee and Zhou, 1999; Kiss et al., 1985).

Neutron and gamma ray transport in both the target assembly and the water phantom were handled by means of the MCNP5 code where mesh tallies were used to determine the flux distributions (Waters, 2002). Statistical errors for the tallies were kept below 5% and the S(α,β) treatment of thermal neutron scattering was used.

2.2. Absorbed dose calculation for BNCT

The absorbed dose from heavy charged particles (hcp) was computed from the neutron flux generated by MCNP5 for each cell tally in the water phantom. Conversion of particle flux to dose was carried out using the conversion factors for hcp interactions (Caswell and Coyne, 1980). The total dose to normal tissue due to hcp was taken as the sum of the 10B concentration, 14N(n,γ)14C and (n,n) reactions of H,C,N and O. The total dose to tumor was computed in the same manner, differing only in the 10B concentration which was set at 30 ppm. The gamma ray flux resulting from both the neutron capture gamma rays and the gamma rays from the Li-target were converted into absorbed doses using the dose conversion factors (Hubbell, 1999). Their sum was designated as the total gamma ray dose to both tumor and healthy tissue. Here, tissue composition was assumed to be: H(11.1%), C(12.7%), N(2%) and O(74.2%) by weight percent for the absorbed dose calculation (Snyder et al., 1975).

2.3. Optimization indices for BNCT irradiation facility

TPD was used for the Optimization Indices for BNCT irradiation facility. Protocol depth (PD) is defined as the depth in the living body where the tumor dose equals its treatable dose when the normal tissue dose equals its tolerance dose. PD(γ) and PD(hcp) for hcp were defined and TPD was defined as the shallower depth between PD(γ) and PD(hcp) (Benguia et al., 2006). In this paper, PD(γ) corresponds to the central axis depth where the dose to tumor from hcp is 15 Gy and the gamma ray dose to healthy tissue is 10 Gy. PD(hcp) is the central axis depth for which the dose to tumor and the dose to healthy tissue from hcp are both 15 Gy. The hcp and gamma ray dose protocols applied for tumor and healthy tissue were taken from the intra-operative BNCT protocol as given in Table 1.

3. Results and discussion

The thick Li-target is defined as a target thickness thicker than the range of protons which produces the same number of neutrons and gamma rays. For the DNU using a thick Li-target, the contaminant gamma-rays should be significantly reduced as reasonably possible. In this case, a Pb layer of about 3 cm thicknesses was used for gamma-ray shielding and was placed between the Li-target and patient. This Pb layer influences the conditions of incident neutrons and gamma rays into the patient, for example, the energy spectrum and its intensity will change according to the thickness of Pb layer. The Pb thickness of 3 cm was optimized using the concept of the TPD and the BDE (Kobayashi et al., 2008). Fig. 2 shows the BNCT-dose components for various incident proton energies with Gaussian distributions. Listed in Table 2 are the TPD, BDE and the necessary proton current obtained.

Table 1

| Dose protocol of the intra-operative BNCT for brain tumor (in physical doses). |
|-------------------|---|---|---|
| hcp              | γ | hcp+γ |
| Treatable dose (Gy) | 15 | * | * |
| Tolerance dose (Gy) | 15 | 10 | * |

* No particular dose is currently specified in the protocol.
for the incident proton energies investigated in this study assuming an irradiation time of 1 h. TPD had almost same value for $\sigma = 0, 10, 20, 40$ keV. BDE slightly increased with higher proton energies. Proton current decreased as the incident proton energy increased. Comparison from former results, the Gaussian energy distribution of the incident proton beam does not influence the dosimetric characteristic of the BNCT irradiation field. The energy fluctuation within $\sigma = 40$ keV for a Gaussian incident proton beam would be acceptable for proton mean energy from 1.90 to 1.95 MeV. The attainable maximum TPD (TPDmax) for a thick Li-target can be narrow down compared to an ideal thin Li-target combined with a suitable BDE thickness. The present estimation will offer some suitable information to determine the gamma ray shielding needed for DNU using Pb and polyethylene BDE. If we want to know the precise thickness of the Pb layer, further simulation calculations are necessary to optimize the relationship between TPD and the thickness of the BDE.

For an actual accelerator system, the stability of proton energy is critical especially for the near threshold $^7$Li($p,p')^7$Be neutron production. The neutron yield and their angular distribution change drastically at this proton energy range. From the preliminary investigation about the influence of the energy distribution in the proton beam, the estimated TPD would be a little shallow but not be significantly different compared to a mono-energetic beam.

An incident proton energy of 1.92 MeV having a Gaussian energy distribution with the standard deviation of 20 keV and a current of 10 mA was selected from the viewpoint of practical conditions such as irradiation time and proton current. The suitable thicknesses of Pb layer as gamma absorber was estimated to be about 3 cm.
The estimated thickness of the polyethylene BDE were about 24 mm for a proton current of 13 mA, and 18 mm for a proton current at 10 mA. The optimum polyethylene BDE thickness and proton current are both dependent on the treatment condition.

The relationship between BNCT and surgery is especially interesting in the case of brain tumors. According to a present protocol for brain tumors irradiated with epithermal neutrons, one or two weeks after the first surgery, BNCT without craniotomy is carried out. It is important to note that for BNCT with surgery (i.e., intra-operative):

1. A large dose can be delivered to deep-seated tumor. This is a big advantage of BNCT with surgery.
2. The inconveniences on patient are usually large from the viewpoint of invasiveness of repeated surgery and the safety in patient transport after the operation.
3. The dependence of the dose distribution on the patient’s position and the beam direction is large.

If we could carry out BNCT with surgery in a hospital immediately after the first surgery, we can have the advantage mentioned in item 1 and avoid the disadvantage of item 2 mentioned above. The problem mentioned in item 3 above would be resolved by on-line dose estimation system. This is an ideal BNCT system for brain tumor.

4. Conclusions

The near threshold \(^{7}\text{Li}(p,n)^{7}\text{Be}\) reaction as a neutron source is feasible with a thick Li-target in liquid form and a proton beam with Gaussian energy distribution from an RFQ is usable for BNCT. This is however dependent on the configuration of the target structure, insulator, cooling system, Pb gamma-ray shielding, polyethylene BDE. For 1.92 MeV proton beam having \(\sigma=20\) keV Gaussian distribution and 1 mm thick target, the TPD (i.e., practical curable depth) would be around 32 mm which is shallower than the 39 mm achievable on the ideal condition of a thin Li-target and a mono-energetic proton beam at 1.900 MeV.

In conclusion, a feasible condition of practical system using liquid Li-target and RFQ proton accelerator is confirmed. This kind of system could offer a possibility for BNCT to be carried out at a downtown hospital all the year round.

References


