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Review

Present status of Accelerator-Based BNCT

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ABSTRACT

Aim: This work aims at giving an updated report of the worldwide status of Accelerator-Based BNCT (AB-BNCT).

Background: There is a generalized perception that the availability of accelerators installed in hospitals, as neutron sources, may be crucial for the advancement of BNCT. Accordingly, in recent years a significant effort has started to develop such machines.

Materials and methods: A variety of possible charged-particle induced nuclear reactions and the characteristics of the resulting neutron spectra are discussed along with the worldwide activity in suitable accelerator development.

Results: Endothermic ^{7}Li(p,n)^{7}Be and ^{9}Be(p,n)^{9}B and exothermic ^{9}Be(d,n)^{10}B are compared. In addition to having much better thermo-mechanical properties than Li, Be as a target leads to stable products. This is a significant advantage for a hospital-based facility. ^{9}Be(p,n)^{9}B needs at least 4–5 MeV bombarding energy to have a sufficient yield, while ^{9}Be(d,n)^{10}B can be utilized at about 1.4 MeV, implying the smallest possible accelerator. This reaction operating with a thin target can produce a sufficiently soft spectrum to be viable for AB-BNCT. The machines considered are electrostatic single ended or tandem accelerators or radiofrequency quadrupoles plus drift tube Linacs.

Conclusions: ^{7}Li(p,n)^{7}Be provides one of the best solutions for the production of epithermal neutron beams for deep-seated tumors. However, a Li-based target poses significant technological challenges. Hence, Be has been considered as an alternative target, both in

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combination with (p,n) and (d,n) reactions. $^{9}Be(d,n)^{10}B$ at 1.4 MeV, with a thin target has been shown to be a realistic option for the treatment of deep-seated lesions.

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1. Introduction

Accelerator-Based BNCT (AB-BNCT) is being viewed worldwide as the future modality to start the era of in-hospital facilities. There are projects in Russia, UK, Italy, Japan, Israel, and Argentina to develop AB-BNCT around different types of accelerators which will be briefly reviewed.

In this article a variety of possible charged-particle induced nuclear reactions and the characteristics of the resulting neutron spectra will be discussed along with different particle accelerators as neutron-producing sources. The focus is in the treatment of deep-seated tumors which require an epithermal neutron spectrum (the epithermal range is defined as ranging from 0.5 eV to 10 keV) at the patient's entrance. Likewise the epithermal neutron flux has to be larger than 10^9 n/cm^2 s. Present efforts to develop such facilities worldwide will be described.

2. Overview of accelerator development for AB-BNCT worldwide

Presently there are several initiatives to develop AB-BNCT. Table 1 gives the present status and performance of the different accelerators for AB-BNCT facilities worldwide. Some of the accelerators are already developed and some are under construction. We include only proton or deuteron machines. There is a first group of accelerators which are already operational, they are mainly low energy machines working stably on relatively low currents and using the ^{7}Li(p,n) reaction although some of them may be upgradable. The exception is the KURRI project which uses a 30 MeV proton cyclotron and Be as a neutron producing target, having to deal with a very hard neutron spectrum. The last three rows describe facilities under development conceived to operate at higher current levels.

3. Different neutron-producing reactions of interest for AB-BNCT

Table 2 lists the reactions considered in this work for AB-BNCT along with some of their properties. It is worth remembering that the Coulomb barriers of protons on common structural materials, like Fe and Cu, are about 5 MeV and hence, in order to avoid inducing radioactivity, it would be desirable to work below that threshold.

3.1. *The endothermic ^{7}Li(p,n)^{7}Be and ^{9}Be(p,n)^{9}B reactions*

The most popular endothermic reaction for AB-BNCT is ^{7}Li(p,n)^{7}Be. The Q-value is −1.644 MeV and the threshold energy for the impinging proton is 1.880 MeV. At this bombarding energy the neutron has about 30 keV kinetic energy in the lab frame. This energy is not very far from the epithermal regime. There are in fact proposals to work in this regime.[9,10] At 1.91 MeV the maximum and average neutron energies are 105 and 42 keV and the maximum and average emission angles are 60 and 28°.[11] This angular confinement ("kinematic collimation") allows for a very efficient utilization of the neutrons in terms of the ratio of utilized neutrons/produced neutrons.

In addition to the kinematics of the reaction, it is important to examine the cross section as a function of the proton energy in the lab which will determine the actual neutron production. ^{7}Li(p,n)^{7}Be shows a very steep rise from the threshold on and a small plateau starting at about 1.93 MeV (reaching a value of 270 mb) before the pronounced resonance at 2.25 MeV (reaching 580 mb).[12] This translates, as examples, into the following values for total thick target Li neutron yield: 6.3×10^9 n/(mA s) for 1.89 MeV and 5.8×10^{11} n/(mA s) for 2.3 MeV proton bombarding energy[11] (see also Table 3).

Working near-threshold would require very little moderation (at 1.89 MeV the maximum neutron energy is 67 keV) but at the same time would impose a very stringent demand on the energy/voltage stability of the accelerator of 0.1% in order to maintain the production rate sufficiently constant. In our studies[13] we have concluded that 2.3 MeV incident proton energy is a very good compromise between an already significant value of the production cross section and still a sufficiently low maximum neutron energy of 573 keV. The minimum neutron energy is 141 keV (at an angle of 180°) and the average energy is 233 keV for a thick target (a thick target is defined as one in which the projectile looses enough energy to cross below the reaction threshold).

To use the ^{7}Li+p reaction would hence demand an accelerator of 2.3 MV "effective" voltage if it is a single-ended machine (the term effective is to indicate that it is not necessarily an electrostatic voltage, e.g., if the accelerator is electrodynamic) or 1.15 MV if it is a tandem (we shall discuss the different accelerator options later on). In addition, the necessary therapeutic thermal neutron flux of the order of 10^9 n cm^{-2} s^{-1} at the tumor position demands relatively high currents (order of tens of mA's needed due to the thick moderator) and here is where the real challenge lies. The high power density deposited in the target material, here metallic Li in the most efficient case, is very high (of the order of 1 kW cm^{-2}) and its cooling represents a challenging technological problem in itself, particularly in view of the rather low melting point (180.5 K) and thermal conductivity (85 W m^{-1} K^{-1}) of Li. The difficulty in keeping the target solid has led to the consideration of a liquid Li target.[5,17] Another non-negligible complication is the fact that the residual nucleus ^{7}Be is radioactive, implying risks associated to target activation and possible system contamination.

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